DONALD BREN SCHOOL OF
ENVIRONMENTAL SCIENCE & MANAGEMENT
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

Mission
Linen Supply
MISSION LINEN & UNIFORM SERVICE

Assessing the Environmental Impacts of Industrial Laundering:
Life cycle assessment of polyester/cotton shirts

A Group Project submitted in partial satisfaction of the requirements for the degree of
Master's in Environmental Science and Management
for the
Bren School of Environmental Science & Management

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As authors of this Group Project report, we are proud to archive this report on the Bren School's website, such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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The mission of the Bren School of Environmental Science & Management is to train professionals with unrivaled training in environmental science and management who will devote unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a yearlong activity, which requires groups of students to conduct focused, interdisciplinary research on scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Thomas Dunne

Tom Dunne

ABSTRACT

Industrial laundering, or the service of collecting, washing and drying, and redistributing rented apparel and linen products, ranks among the top industrial contributors of greenhouse gas emissions in the United States on the basis of every dollar spent in the economy. Furthermore, the creation of textiles and apparel products cleaned by this industry draws heavily on natural resources that can adversely impact both the natural and human environments. The client, Mission Linen Supply, provides uniform rental and laundering services to businesses throughout the western United States. With Mission Linen Supply serving as a model for the broader industry, this group examines the life cycle energy and water inputs and assesses the climate change impacts of garments used in this business. To accomplish these goals, a Life Cycle Assessment (LCA) of a popular rental item—a button-up, uniform shirt consisting of 65% polyester and 35% cotton—is performed. Based on the results and conclusions of the study, the group provides recommendations that can help Mission Linen Supply reduce resource use within and beyond its operations. Moreover, the findings from this unique study add to the growing body of knowledge in the international LCA community and can encourage other organizations in related industries to quantify their resource use and reduce the environmental impacts of their products and services.

EXECUTIVE SUMMARY

Introduction

Industrial laundering, or the service of collecting, washing and drying, and redistributing rented apparel and linen products, ranks among the top industrial contributors of greenhouse gas emissions (GHG) in the United States on the basis of every dollar spent in the economy. Furthermore, the creation of textiles and apparel products cleaned by this industry draws heavily on natural resources that can adversely impact both the natural and human environments. As the earth's population increases and seeks a higher standard of living, the demand for apparel and laundering services will grow—increasing pressure on resources. This group project seeks to better understand the life cycle environmental impacts of textile creation and laundering activities and develop feasible recommendations based on the study's findings.

Mission Linen Supply, an industrial linen and uniform rental and supply company based in Santa Barbara, California, commissioned this Bren Group Project to help identify ways to improve its environmental performance. The primary goal of this project is to determine the environmental impacts of one of Mission Linen Supply's main products throughout its life cycle, focusing on energy and water use and the global warming potential from GHG emissions. In addition, the objectives are to identify the specific processes in the product's life cycle that contribute the greatest to the resource use and environmental impact categories being examined and recommend areas for improvement. The recommendations resulting from this project can help the client with decision-making and strategic planning in the areas of process improvements leading to cost savings, better positioning the company for compliance with anticipated government regulations, and attracting new clientele with marketing initiatives that highlight improvements in environmental performance.

Method

This project employs a life cycle assessment (LCA) of one of Mission Linen Supply's most popular rental items—a button-up, short-sleeve, uniform work shirt made of 65% polyester and 35% cotton. This LCA study quantifies the energy and water inputs and the assesses the climate change impacts throughout the life of the shirt, from raw material acquisition and manufacturing of the shirts to the laundry and landfill disposition when the shirt is retired from service. Although the client operates twenty-eight laundering facilities in the Western U.S., this study only examines the four of these plants to derive an average baseline for its operations.

This study follows the principles and guidelines of ISO, the International Organization for Standardization, specifically the ISO 14040 series, which is the most widely accepted standards for performing LCAs in the professional LCA community. For this study, the project team collected both measured data of the client's processes and secondary data, among them professional LCA databases and published, peer-reviewed studies. To model the entire life cycle of the client's rental shirt, the GaBi LCA Software was utilized.

Results & Discussion

Assuming fifty-two washes, which is the typical usage rate in a two year lifespan of a 65% polyester/35% cotton shirt at Mission Linen Supply, the total life cycle energy use of the shirt is 102 MJ (equivalent to burning 0.8 gallons of gasoline), cumulative water use is 2,729 liters—2,276 liters of non-consumptive use and 453 liters of consumptive use—(or roughly 15 average bathtubs), and contribution to global warming is 5.7 kg CO_2-equivalent (or the consequence of burning 1 gallon of propane). Of the three distinct phases, the amount of resources used and contribution to global warming is the highest in the shirt's use phase, accounting for 64% of energy use, 72% of water use, and 76% of the global warming potential. The shirt creation phase accounts for 36% of the energy use, 27% of total water use, and 24% of the global warming potential. Disposing of the shirt contribute less than 1.5% in the three impact categories examined above. These results are consistent with previous apparel LCAs that have reported the shirt use phase as having a higher environmental impact than the shirt creation phase.

One common theme in the LCA results is the relationship between energy and water use. Energy and water go hand-in-hand, as energy production involves intense water use—for activities like pumping crude oil, generating steam that turns turbines, and keeping power plants cool. Conversely, treating and transporting water requires intense energy use. It is noted that processes that are energy intensive also resulted in higher water usage, since upstream resource use is taken into account in this LCA.

Recommendations & Conclusion

This study reveals a number of "hot spots" in resource use and environmental impact throughout the shirt's life cycle that can be improved through operational adjustments. Much of the upstream (shirt creation) recommendations concern fiber choice and vendor selection. Polyester production and yarn manufacturing consume the highest amount of energy, while cotton cultivation and production requires the most water. Utilizing recycled polyester fibers and sourcing sustainably grown cotton can reduce the net resource use and environmental impacts compared to the use of virgin polyester fiber and conventionally grown cotton. In the shirt use phase, the four main processes—water heating, washing, drying and transportation (or distribution and pick-up) of garments—contribute nearly equally to energy use and global warming, while the transportation process uses the least amount of water. Recommendations to improve MLS's processes include the installation of equipment meters to monitor efficiency and consider the replacement of outdated equipment with more efficient versions. Regular equipment maintenance can also increase its efficiency. Since garment laundering requires a substantial use of hot water, installation of solar water heating systems at the facilities with high insolation levels can be an economically feasible option, especially with the availability of state cash rebates and federal tax credits.

Mission Linen Supply may use this information to further understand the variety of resource consumption rates across its operations and to make better-informed decisions for improvement measures. Further, the report offers broader recommendations to improve the ability of the organization to successfully implement and maintain environmental initiatives. The report authors advocate sharing the results with the broader textile rental and linen supply industry to encourage upward scalability. In this vein, life cycle thinking can help create a "blueprint" for systemic industry improvements in environmental performance.

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ACRONYM GUIDE

EDIP:	Environmental design of industrial products
LCA:	Life cycle assessment
MLS:	Mission Linen Supply
GaBi:	LCA software tool produced by PE International. Shortening for German *Ganzheitliche Bilanz*, which means Holistic Balance.
GHG:	Greenhouse gas
GWP:	Global warming potential
IPCC:	International Panel on Climate Change
WMO:	World Meteorological Organization
SETAC:	Society of Environmental Toxicology and Chemistry
Eol:	End-of-life
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment

DEFINITIONS

Characterization	The second step of an impact assessment where environmental interventions grouped into specific impact categories are calculated to the same unit and aggregated into a single score, the indicator result.
Characterization factor	Commonly referred to as "equivalency factors," science-based conversion factors that convert and combine the LCA results into representative indicators of human and ecological health.
Classification	The first step of a life cycle impact assessment and is the process of assigning inventory outputs into specific environmental impact categories.
Cradle-to-gate	Cut-off criteria used to define the study's system boundary; Cradle-to-gate includes all processes from the raw material extraction through the production phase (gate of the factory); used to determine the environmental impact of the production of a product. For this study, cradle-to-grave encompasses raw material acquisition of cotton and polyester through to disposal of the shirt in landfill.
Cradle-to-grave	Cut-off criteria used to define the study's system boundary; Cradle-to-grave includes the material and energy production chain and all processes from the raw material extraction through the production, transportation and use phase up to the product's end of life treatment. For this study, cradle-to-gate encompasses raw material acquisition of cotton and polyester through to final shirt assembly.
Elementary flow	The material or energy entering or leaving the system being studied, which has been drawn from the environment without previous human transformation or discarded into the environment without subsequent human transformation
End-of-life	End-of-life, abbreviated EoL, refers to the stage in a product or service's life cycle in which it is deemed no longer useful for its intended purpose
Environmental	The elementary flows that come from processes, such as

intervention	emissions, chemical outputs, etc.
Flow	Represents the movement of material or energy between processes in a system. In LCA terminology, may be elementary or intermediate, definitions for both included in this list.
Impact category	The classifications of human health and environmental effects caused by a product or service throughout its life cycle.
Indicator result	Established in the characterization step, values calculated by multiplying the relevant *environmental interventions* by their corresponding characterization factors
Intermediate flow	Flows of material and energy between *processes* within the study's system boundaries—disparate from elementary flows, which enter and exit the system.
Plan	A term for the GaBi representation of the system being studied, made up of processes and flows.
Process	A term for the GaBi representation of the actual processes taking place in the production of a service or product.
Product system	A collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product
Unit process	A gate-to-gate process containing only the data of one specific process step and not including intermediate flows. Also referred to as 'basic process' in the ISO standard.

Throughout this report, we have endeavored to maintain consistency of meaning with the LCA terminology promulgated by the ISO 14040 series of standards. To aid report readers, we have included this list of definitions, adapted from the U.S. Environmental Protection Agency, *Life Cycle Assessment: Principles and Practice* (May 2006); Guinée, et al., *Handbook on life cycle assessment: Operational guide to the ISO standards* (2002); and the *GaBi Education Handbook* published by PE International. Full reference information is included in the References section of this report.

1. PROJECT MOTIVATION

The linen supply and industrial laundering industries employ more than 132,000 people nationwide and have combined annual revenues of approximately $12 billion (LaundryESP, 2010). This sector consumes significant amounts of resources, particularly energy and water. It also creates pollutants indirectly from energy generation and directly through the use of cleaning chemicals in the washing process and the removal of chemicals and soiled matter from the laundered garments. Based on an economic input-output life cycle assessment model developed by Carnegie Mellon University's Green Design Institute, the industrial laundry sector was ranked as the second highest energy consuming and greenhouse gas (GHG) emitting industry, as well as the third highest water consuming industry in 2002 (Carnegie Mellon, 2008). Thus, laundering companies that meet regional regulations on effluent discharges of organic pollutants can still significantly impact the environment.

In addition to the laundering of linen and garments, the creation of textiles also imposes a substantial environmental burden. Fabrics made from both natural and synthetic materials require the use of numerous resources. The cultivation and harvesting of cotton, for example, demand significant amounts of water, fertilizers, chemicals, and energy. Moreover, fossil fuel-based petrochemicals are the main inputs for the manufacturing of polyester and other synthetic fibers. In a report produced for MADE-BY, a European non-profit with the mission to improve social and environmental sustainability in the apparel industry, environmental consultants Brown and Wilmanns classified conventional cotton and virgin polyester as the worst and second worst fiber choices, respectively, in an overall ranking of common textile fibers citing their performance in impact categories like GHGs, human toxicity, eco-toxicity, energy input, water input, and land use (MADE-BY, 2009). Creating textiles involves a long chain of heterogeneous operations, including yarn manufacturing, weaving, dyeing, and cutting and sewing. These textile manufacturing processes generate large volumes of waste and use significant amounts of water. At the end of their useful lives, the merchandise is usually disposed of in a landfill. The UK averages nearly 40 kg per person of textile waste per year, and of this, 30 kg goes to landfill (Cupit, 1996). The sheer volume of textile waste highlights the many resources that have gone into production and use.

2. MISSION LINEN SUPPLY

Mission Linen Supply (MLS) is primarily a linen and uniform rental business. The company serves 50,000 customers and launders 12 million pounds of textiles at 28 wash-and-dry facilities around the western U.S., including one near downtown Santa Barbara. Mission Linen Supply has several motivations for this group project, including: 1) the potential for cost savings from greater efficiencies throughout the shirt's life cycle; 2) the potential for anticipating future legislation and regulation specific to the textile rental industry in California and thus facilitating timely, well-researched and sound decisions to achieve compliance; 3) improving product and equipment design; and 4) the option to apply the report results and recommendations towards efforts for creating a competitive marketing advantage through environmental product differentiation.

MLS also aims to be an industry leader in preparation for regulatory pressures especially in the areas of water and energy usage. MLS would like to anticipate regulations similar to or stemming from California's Assembly Bill No. 32 legislation to reduce GHG emissions from their operations (California Department of Water Resources). The company has facilities in five U.S. states, each with unique and evolving water usage policies to consider. The western/southwestern region of the country, California in particular, faces water scarcity issues that will likely prompt stricter water use guidelines (California Department of Water Resources, 2009). Industrial laundering and textile creation are water-intensive industries. Thus, MLS is interested in insulating their operation as much as possible from any future hikes in water prices. Aramark, a competitor of MLS, has engaged in a number of environmental initiatives to date. Commissioning this LCA is one component of MLS' multi-faceted effort to remain competitive.

MLS cites a number of initiatives that have helped the company reduce its environmental impact. These initiatives include the installation of wastewater pretreatment systems, proper equipment maintenance as per manufacturer's specifications, which achieves greater efficiencies, and the installation of efficiency-improving technologies at some laundering facilities. But to advance its environmental performance even further, MLS identified the need for better supply chain oversight and stronger understanding of life cycle impacts of their service. Therefore, MLS chose to commission a Bren Group Project to conduct a LCA of its high volume rental garment—the 65% polyester/35% cotton button-up uniform shirt—with 200,000 pieces currently in service. The LCA would be one means within a broader effort for advancing the company's environmental performance.

3. PROJECT OBJECTIVES

The project's main goal is to quantify and assess the life cycle environmental impacts of a 65% polyester/35% cotton button-up, uniform shirt and to generate useful recommendations for MLS to improve their environmental performance. To accomplish these goals, the project will identify the life cycle processes with the largest environmental impacts, focusing on flows of energy, water, and GHG emissions.

Following completion of the LCA, the team applied the better understanding of life cycle environmental impacts into actionable recommendations for operational and design improvements feasible for MLS in the near-, intermediate-, and/or long-term. Recommended actions were guided by a thorough literature review of the industry and LCA practice. More specifically, project objectives are to:

- Quantify energy use and water consumption associated with fabric creation, garment manufacturing, transportation, laundering, and garment disposal, and assess its the environmental impacts from GHG emissions;
- Identify processes in the life cycle of the garment that contribute the most to GHG emissions and consume the greatest amount of energy and water;
- Recommend changes that will yield improved environmental performance;
- Identify regulations and industry trends for MLS to keep on the company's horizon.

4. PROJECT APPROACH: LIFE CYCLE ASSESSMENT

To examine the environmental performance of MLS's operations and the products they purchase, a life cycle assessment (LCA) was performed. LCA is a method to systematically quantify and assess the resource use and environmental impacts of an industrial system through its entire life cycle, from raw material acquisition, through manufacturing, use and disposal (i.e. cradle-to-grave), as it relates to the defined goal and scope of the project (ISO 14040, 2006). This systems perspective provides a comprehensive view of the environmental impacts of MLS's products and operations at various points in the life cycle and helps prevent process improvements from shifting environmental burdens from one stage to another (EPA, 2006).

4.1 LIFE CYCLE ASSESSMENT FRAMEWORK

This study follows the principles and guidelines of ISO 14040 series promulgated by the International Organization for Standardization, which is the most widely accepted standards for performing LCAs in the professional LCA community. Using the LCA framework, this study follows the four steps outlined below (ISO 14040 and 14044, 2006):

4.1.1 GOAL AND SCOPE DEFINITION

The goal is defined by stating the objectives and intended applications of the study. To elucidate the scope of the study, a functional unit is defined to describe the performance characteristics of the system being considered and for quantifying inputs and outputs. A functional unit allows for comparison between the studies of different systems as long as all systems serve the same function and are quantified using the same reference flow. The scope also describes the temporal (i.e. age of the data), geographical and technology coverage (i.e. weighted average of actual technologies, best available technology, etc.) (Guinée et al., 2001).

4.1.2 LIFE CYCLE INVENTORY (LCI) ANALYSIS

This step of the LCA involves the identification, collection, calculation and validation of data for each unit process within the system boundary. A process flow diagram is drawn to capture all of the unit processes of the product system, illustrating the inputs and outputs, or elementary flows (i.e. material or energy entering or emissions leaving a unit process) and the movement of products between unit processes, or intermediate flows (see **Figure 1**).

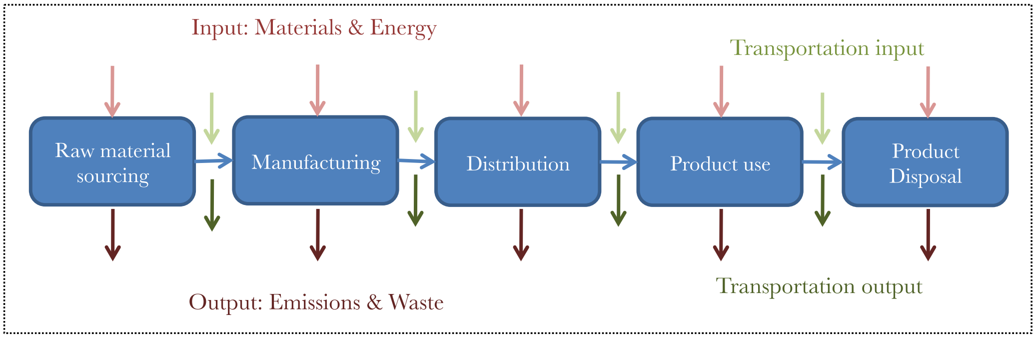

Figure 1 Sample process flow with generalized unit processes (Adapted from Geyer, 2011a)

Once the inputs and outputs are identified, data is collected from reliable sources to determine the quantities needed to fulfill the functional unit requirements and aggregated to a resulting inventory of inputs and outputs. The method of itemizing inputs and outputs for each unit process is called the process-based LCA approach. To check the validity of resulting life cycle inventory (LCI), validation can be done by comparing the inventory data with other published sources or by performing an economic input-output LCA. Economic input-output, sometimes abbreviated "EIO," is another form of LCA that uses the economic value of life cycle processes to represent or capture relative environmental impacts.

4.1.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Once an inventory of the resource use and emissions is quantified for the entire life cycle of the system, an impact assessment is performed to evaluate the significance of potential environmental interventions. First, results of the LCI are classified into a corresponding impact category, such as climate change, acidification, stratospheric ozone depletion, etc. Subsequently, characterization factors are applied to convert each impact category to common units that can be aggregated into indicator result categories for determining the magnitude of potential environmental impact. (See **Figure 2** for an example depiction of classification and characterization.)

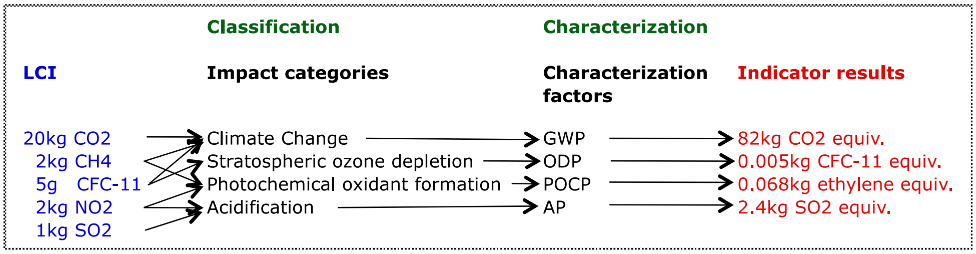

Figure 2 Example of the Classification and Characterization step in LCA (Source: Geyer, 2011b) *(Note: GWP = global warming potential; ODP = ozone depleting potential; POCP = photochemical ozone creation potential; AP = acidification potential)*

To achieve the goal of this study, only energy and water use will be quantified and the only indicator result examined is global warming potential (GWP) from GHG emissions reported in kg CO_2 equivalent. Many characterization metrics are available through the GaBi software and produce similar results. This LCA study use the Environmental Design of Industrial Products (EDIP) 2003 LCIA methodology for characterizing GHG emissions, which takes into account the actual environment receiving the elementary flows in an attempt to increase the relevance of the calculated impact assessment. This LCA excludes discussion on other impact categories, such as eutrophication, acidification, and human toxicity because procedures to accurately quantify these data are still being developed. For example, characterization factors for acidification or eutrophication potential are location-dependent and including regional differences in the LCA model is problematic (Guinée et al., 2001). In addition, some inputs, such as the chemical composition of soiled material on dirty shirts, vary and cannot be quantified for the laundering phase. Moreover, regulations on effluent for wastewater discharge are already in place for industrial laundry facilities so pollution levels are being controlled, whereas GHG emissions are not currently regulated.

4.1.4 INTERPRETATION

In the interpretation phase, the LCA results are examined for completeness, consistency and an uncertainty analysis is performed. Subsequently, the knowledge gained through the LCA study is summarized and recommendations are provided to the client's decision-makers in accordance to the goal and scope of the project.

4.2 GABI LIFE CYCLE ASSESSMENT SOFTWARE

To assist with life cycle modeling of the project's product system, the GaBi 4 modeling software is used. Developed by PE International, a sustainability software and consulting company based in Stuttgart, Germany, GaBi 4 is one of the two most robust and prominent LCA modeling programs on the market. GaBi (an acronym for *Ganzheitliche Bilanz*, German for Holistic Balance) provides the tools to manage large datasets, model product life cycle systems, calculate energy and mass balances and interpret the results of the life cycle balances (GaBi, 2006).

GaBi functions by connecting and balancing *processes*, *flows*, and *plans*. GaBi's *processes* represent actual individual or a group of processes or technical procedures. *Flows* represent actual energy or material inputs and outputs. Washing of garments, is an example of a process with input flows of soiled shirts, water, energy, etc. and output flows of cleaned shirts, used water, indirect emissions from energy use, etc. *Plans* assemble processes in the product system, which can visually display a life cycle stage. As an example, the stage of creating a garment is a *plan* that includes raw material acquisition, fabric manufacturing, dyeing, cutting and sewing, among other processes.

The GaBi software integrates ISO 14040 and 14041 guidelines relevant to its system functionality. The software also comes with a basic database of certain flows, processes and plans. In addition, the Bren School supplements the basic GaBi database with its license to a number of PE's professional databases as well as the EcoInvent LCI database (EcoInvent, 2007). These databases contain information on various industries, individually termed datasets, and are based on industry and technical literature sources and compiled by internationally renowned research institutes and LCA consultants. Processes and datasets provided through the Bren resources were used only in the case that they were applicable to the study. Otherwise, the study employed raw and secondary data collection and the crafting of unique processes.

In addition to supporting the development of the LCI, GaBi also performs a life cycle impact assessment of potential environment impacts by assigning (*classifying*) and modeling (*characterizing*) the LCI data into life cycle indicator results. The classification and characterization data utilized by the software come from data published by ISO, the Society of Environmental Toxicology and Chemistry (SETAC), the World Meteorological Organization (WMO) and the International Panel on Climate Change (IPCC). The resulting indicator value is provided by the Environmental Design of Industrial Products (EDIP), among other life cycle impact assessment methodologies (GaBi, 2006).

5. LIFE CYCLE ASSESSMENT IN PRACTICE

The portions of this study that are unique among published LCAs can assist efforts to further life cycle research related to the apparel and textile industry. In industry, especially those companies or organizations looking to better understand the environmental impacts of a 65% polyester/35% cotton garment may find this study useful. While a number of LCAs have been conducted on apparel products, the type of fabric and specific processes employed limit the applicability of the results to scenarios with a very specific set of similar conditions. The applicability of this study to other studies' distinct scenarios will hinge on a thorough comparison of inputs and assumptions, but in situations where these variables are deemed similar enough for practical application, this report can help others contextualize the environmental impacts of the processes within their supply chains. Further, this report may provide guidance and a point of comparison for subsequent LCAs. Finally, and most broadly, this work highlights the environmental impacts of the textile and industrial laundering sectors. Communication stemming from this report would then, in effect, raise awareness of the resource use and environmental impacts of these industries.

6. LIFE CYCLE GOAL AND SCOPE DEFINITION

The following sections detail the goal and scope of the LCA performed in this study.

6.1 GOAL AND SCOPE

The aim of the project is to examine and recommend ways to reduce the life cycle resource use and environmental impacts of MLS's laundry operations. MLS launders linens and uniforms made of various types of fabrics and used for different applications. Due to time and resource constraints, this LCA evaluates the highest volume MLS garment, a 65% polyester/35% cotton button-up, short sleeve industrial work shirt. Because all laundered shirts are created, laundered, and disposed of somewhat similarly to the polyester/cotton shirt, the choice of this fabric blend enables the evaluation of both natural and synthetic fibers, which can be used as a basis to assess other types of garments laundered at MLS. Further, cotton and polyester are the most commonly used natural and synthetic fibers, respectively, in garments worldwide.

6.2 FUNCTIONAL UNIT

The functional unit is defined as 52 days' use of a short sleeve shirt, laundered each time after use, over two years. This type of shirt is washed every other week and has an average lifespan of 2 years at MLS.

6.3 REFERENCE PRODUCT

The product being examined is a 227 gram 65% polyester/35% cotton button-up short sleeve industrial work shirt, which includes a collar and two pockets. (See **Figure 3**).

Figure 3 The 65% polyester/35% cotton shirt of this study
Image Source: Red Kap

Although the shirt also comes with nine plastic buttons (six on placket, one on collar, and two on pockets), an identification label stitched inside the collar, and is sewn together with thread, these items are excluded from the LCA. This decision is founded on resource and time constraints of the study and, additionally, as the life cycle resource consumption of these items was determined insignificant in a streamlined LCA on polyester trousers commissioned by Marks & Spencer (Collins and Aumônier, 2002).

6.4 DATA SOURCES AND QUALITY

To produce the most accurate LCA possible, the group obtained resource input and output data from MLS's actual operations. When raw data was inaccessible, the group relied on the highest quality secondary data available. Although the Bren School holds licenses to a number of industry datasets in GaBi, additional datasets were needed to fulfill the boundaries of this study, particularly those related to textile and apparel production and industrial laundering operations. Therefore, several other sources of information were consulted. **Appendix A: Data Quality Assessment** shows the specific sources of data for each process, data quality and uncertainties, and additional notes.

The following raw and secondary data sources were employed. Full reference information is cited within the report where applicable.

- Data and standard operational processes measured and recorded by MLS from operational years 2009 and 2010;

- Specification sheets for MLS's equipment;
- Information gathered from MLS's suppliers for the cradle-to-gate processes of shirt creation;
- GaBi Professional database;
- EcoInvent v.2 LCI database;
- Peer-reviewed literature and LCA studies/reports on textiles and/or apparel, including the following:
    - 2008 master's thesis on the environmental benefits from reusing clothes, prepared by Laura Farrant.
    - 2007 report published by the Danish Environmental Protection Agency—EDIPTEX: Environmental assessment of textiles—mainly based on Danish processes and data;
    - 2004 LCA of cotton towels published in the Green Chemistry journal for data on typical mass loss during different processes in the shirt creation phase; and
    - 1993 LCA report for a woman's knit polyester blouse prepared for the American Fiber Manufacturers Association by Franklin Associates, LTD.
- "Bren Grid Model: Cradle-to-Plug Process Inventory for Electricity Generation," Brandon Kuczenski; California energy grid mix extrapolated from the Western Energy Coordinating Council (WECC) and GaBi electricity flows (Kuczenski, 2010);
- EMFAC Burden analysis, 2007 calendar year annual statewide average, modeled by Brandon Kuczenski; California Air Resources Board's emissions factors (EMFAC) for transportation (Kuczenski, 2010);
- California Department of Water Resources, State Water Project Analysis Office, Division of Operations and Maintenance, Bulletin 132-97, April 1997;
- PIER Report: Refining Estimates of Water-Related Energy Use in California, December 2006 (California Energy Commission, 2006).

6.5 SYSTEM BOUNDARY

The system boundary describes the unit processes that are included and excluded from this LCA. Although the system of study encompasses all processes from raw material extraction for shirt creation through the disposal of shirts, certain inputs were omitted due to the time and resources available to the group. This study excludes capital equipment, buildings, vehicles and maintenance, overhead and labor, packaging, shirt buttons, and ancillary and scrap materials. The system boundary is indicated for each unit process.

6.6 ALLOCATION

Some unit processes are multifunctional as their output flows consist of more than a single product (e.g. the process of cotton production creates cotton fibers and cottonseeds) and their input flows may include recycled intermediate flows from other processes (e.g. some recycled water is used in MLS's laundering). In these situations, an appropriate allocation procedure was applied and clearly disclosed for partitioning the input and output flows and environmental interventions to the relevant co-products or functions under study.

6.7 GEOGRAPHICAL, TEMPORAL AND TECHNOLOGICAL SCOPES

To produce the most relevant LCA possible for MLS, the most geographically, temporally and technologically relevant data were collected whenever possible. This study incorporated the most recent country, regional, or company-specific data based on actually processes when the data was obtainable. Differences in the coverage of the stated characteristics are disclosed in the report.

7. LIFE CYCLE INVENTORY

The following sections detail steps in the life cycle inventory (LCI).

7.1 PROCESS FLOW DIAGRAM

To collect data and take inventory of the product system in study, a process flow diagram is drawn. (See **Figure 4** below).

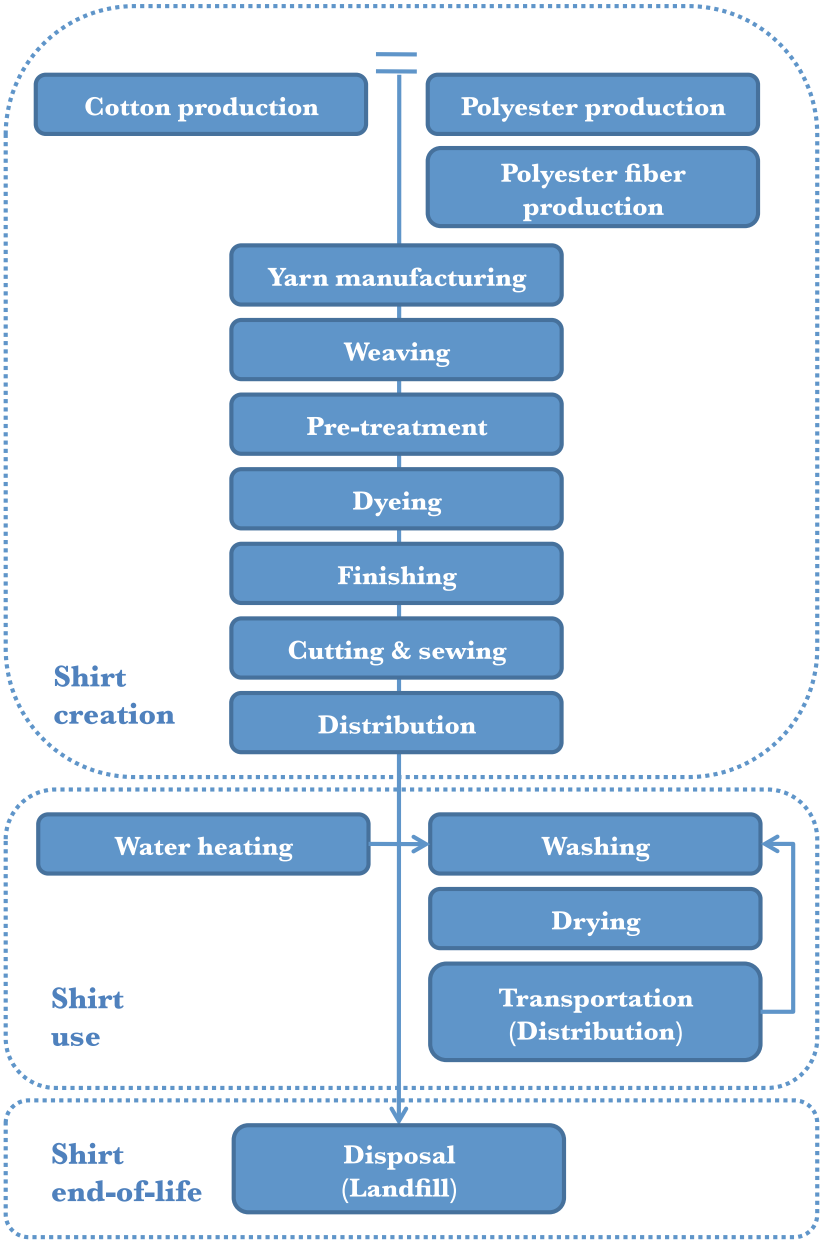

Figure 4 Process Flow Diagram of 65% polyester/35% cotton shirt (Adapted from Farrant, 2008)

7.2 PRODUCT SYSTEM DESCRIPTION AND DATA SOURCE

The product system is divided into three main phases: shirt creation, use (or laundry), and end-of-life (or disposal). Within each phase are individual processes discussed below as relevant to the LCA.

7.2.1 SHIRT CREATION PHASE

MLS sources 75% of their 65% polyester/35% cotton shirts from a supplier in Mississippi, which acquires fabrics from a textile mill in South Carolina. The process diagram for the shirt creation phase was assembled based on the processes of this company. However, due to time constraints the detailed input and output data used in this LCA originated from other secondary sources as further defined in the following sub-sections. Although several processes generate co-products, such as fiber or fabric scrap material that can be recycled, the supply chain partner in charge of shirt assembly does not do so regularly largely due to lack of economic incentive. Therefore, 100% of the environmental burden is allocated to the main product of making a shirt. The only exception is the cotton production process, where an economically significant co-product is generated and regularly used for other purposes.

7.2.1.1 COTTON PRODUCTION

The production of conventionally grown cotton requires significant resources, including irrigated water, synthetic fertilizers, pesticides, and energy, among other inputs during its approximately 150 to 180 day growing season—the longest of any annually planted crop in the United States (Cotton.org). Depending on the location of cotton cultivation and crop management practices, crop yields and resource consumption can vary significantly from country-to-country or region-to-region. Because the textile mill in this LCA sources its cotton from Tennessee or Texas, (personal communication with representative at Milliken), this unit process used cotton production input and output data from EcoInvent's US average dataset, as opposed to the other available option, a global average. The system boundary of cotton production begins after the harvest of the preceding crop and includes cotton cultivation, harvest, ginning and the agricultural infrastructure and operations of buildings and machinery. The only co-product produced in this process is cottonseed for which economic allocation of inputs and outputs are applied to cotton fibers (87%) and cottonseeds (13%).

7.2.1.2 POLYESTER PRODUCTION

For polyester production, this study uses the aggregated input and output flows available in the GaBi professional database for polyethylene terephthalate granulate (PET, via Dimethyl terephthalate (DMT)), which includes the processes from fossil fuel extraction through PET granulates manufacturing. The source of PET granulates was not disclosed by MLS's suppliers. Thus, the study relies on data available through GaBi, which referenced Germany's processes. For the purposes of modeling the shipping of the PET granulates, it was assumed they are sourced from China and shipped to the port of Long Beach, CA before being trucked to Tupelo, MS. Capital equipment and maintenance, overhead and labor are excluded from the system boundary.

7.2.1.3 POLYESTER FIBER PRODUCTION

This unit process includes all operations after PET production to the manufacturing of polyester filament for shipment to the fabric mill. Input data for this process was drawn from Franklin Associate's LCA study of a woman's polyester blouse (Franklin Associates, 1993). This study excluded capital equipment, space conditioning, support personnel requirements and miscellaneous materials and additives.

7.2.1.4 YARN MANUFACTURING

This process includes the carding, combing and spinning of the cotton fibers and polyester filament into yarn. The textile mill studied in this LCA sources its polyester fibers both domestically and internationally; however, LCI data for a 65% polyester/35% cotton yarn was available only from the EDIPTEX study based on data from Danish textile spinning mills. The LCI includes energy consumption for the spinning line and air conditioning and the fiber waste generated during the spinning process. Although the fiber waste can potentially be used for lower quality yarn, it is assumed that the fiber is not re-circulated. (*It should be noted that in practice, yarn manufacturing through fabric finishing all takes place in South Carolina. However, the LCI data for these processes were all obtained from the EDIPTEX study. The*

EDIPTEX study modeled production data mainly from Danish companies. However, to improve the accuracy this LCA study, the 2007 US average electrical grid mix was used for all processes that consumes electrical energy. The system boundary excludes capital equipment and maintenance, overhead, labor and the production of chemicals.)

7.2.1.5 WEAVING

The step is weaving the yarn to form fabric. The EDIPTEX study used data from modern weaving mills with closed-off high-speed air jet looms.

7.2.1.6 PRE-TREATMENT

Prior to fabric dyeing, fabric must be pre-treated to remove wax, pesticide residue, and defoliation agents from the cotton and lubricating oils from polyester yarn production. The fabric is also scoured in an alkaline solution under high pressure and temperature. In addition, since cotton fibers generally contain natural coloring, bleaching is required to obtain clear whites for the finished fabric or in preparation for dyeing.

7.2.1.7 DYEING

As defined in the EDIPTEX study, dyeing is carried out in two steps to accommodate different properties of cotton and polyester. Cotton dyeing takes place in a vat or reactive dye and polyester uses dispersion dyes. Processes in this step include the use of carrier solvents and dyes without heavy metals.

7.2.1.8 FINISHING

Finishing the fabric improves the presentation, feel and performance of the textile. For this study, finishing included the treatment of a softening agent to improve the sewability of the fabric.

7.2.1.9 CUTTING & SEWING (MAKING UP)

At this point, fabric is shipped to either Dominican Republic or Haiti where reams of fabric are cut and sewn into a shirt by a combination of mechanized and human labor. Travel distances between the fabric mill and the two cut-and-sew operations are relatively close so only the distance from South Carolina to Miami, Florida to Port-au-Prince, Haiti and back was modeled.

7.2.1.10 DISTRIBUTION

After the garments are created, they are shipped back to MLS's supplier's headquarters in Tupelo, Mississippi, before being transported to one of MLS's main distribution centers in Chino, California.

7.2.2 USE (OR LAUNDRY) PHASE

MLS initially supplies its customers with eleven clean work shirts. Thereafter, ten used garments are simultaneously picked-up and dropped-off every other week. The average life span of a work shirt is two years; therefore, this model assumes the shirt is laundered 52 times.

Upon arrival at MLS's laundry facility, used shirts are hand sorted by garment and fabric type and by the level of cleanliness. Subsequently, they are washed in large batches following wash formulas that specify the exact quantities of hot and cold water, detergents, other chemicals injected into the washer and the duration of the cycle. (*It should be noted that for the laundry phase, the LCI only includes data on energy and water use. It does not include detergent and chemical data and their associated toxicological impacts or the miscellaneous chemicals washed from soiled garments.)* To provide hot water, a boiler operates eight hours a day. Some boilers feature heat recovery systems, and a number of MLS's facilities operate on-site water recycling systems that removes dissolved solids from used water so it can be reused for the washing phase. After the wash cycle, cleaned shirts are dried in either a tunnel dryer or an industrial-scale dryer and an individual steam press. Finally, the freshly laundered shirts are once again distributed to MLS's clients. For shirt distribution, MLS operates step vans fueled by gasoline. This model utilized data from the EMFAC Burden analysis, 2007 calendar year annual statewide average (Kuczenski 2010). The model utilized a light-heavy duty (LHD) truck, which is up to 14,000 pounds gross vehicle weight rating (GVWR). This assumes an average payload of 1.37 metric tons with a 30% empty fraction. The system boundary of the use phase excludes capital equipment and maintenance, overhead and labor.

7.2.2.1 MLS FACILITIES

MLS operates twenty-eight laundering facilities in several Western states. This study models only four of these facilities, selected for their range of laundry processes, equipment utilized, and the volume of laundered 65% polyester/35% cotton shirts. Each MLS facility was independently modeled in separate plans in GaBi, so resource consumption and environmental impact comparisons could be made between the different facilities. However, a weighted facilities average based on the volume of shirts laundered at each facility was also calculated. The system boundary excludes wastewater treatment systems at the plants and any laundry conveyance machinery.

7.2.2.1.1 CHINO, CALIFORNIA FACILITY

The Chino facility is located in southern California and on average processes about 90,000 pounds of laundry per day. Of the total laundry, the facility washes about 10,000 pieces of 65% polyester/35% cotton uniform shirts daily on average. A typical load of this type of shirts goes through an Elli-brand 450 lb washer, followed by a Colmac-brand Finishing Tunnel. This facility is highly automated and operates with the most laundry conveyance machinery among the facilities.

7.2.2.1.2 SACRAMENTO, CALIFORNIA FACILITY

The Sacramento facility is located in northern California and on average processes about 106,700 pounds of laundry per day. Of the total laundry, the facility washes about 16,000 pieces of cotton/polyester uniform shirts daily on average. This is the largest of the four facilities examined by this study. A typical load of cotton/polyester shirts goes through an Ellis 450 lb washer, followed by a four minute conditioning step in a CLM 400 lb gas tumbler and the Colmac Triple Buck Shirt Press, which can process about 240 shirts per hour. Alternatively the shirts go through the Colmac Finishing Tunnel 2000-G after the wash step. It was assumed this occurs half of the time.

7.2.2.1.3 SANTA BARBARA, CALIFORNIA FACILITY

The Santa Barbara facility is located in southern California and on average processes about 21,500 pounds of laundry per day. Of the total laundry, the facility washes about 290 pieces of cotton/polyester uniform shirts daily on average. This is the smallest of the four facilities examined by this study. It is also considered one of the oldest facilities, containing relatively older machinery. A typical load of cotton/polyester shirts is washed in an Ellis 450 lb washer, followed by a four minute conditioning step in a CLM 400 lb gas tumbler and the Colmac Triple Buck Shirt Press, which can process about 240 shirts per hour.

7.2.2.1.4 OCEANSIDE, CALIFORNIA FACILITY

The Oceanside facility is located in southern California and on average processes about 40,000 pounds of laundry per day. Of the total laundry, the facility washes about 1,000 pieces of cotton/polyester uniform shirts daily on average. A typical load of cotton/polyester shirts either goes to a 675 lb or 900 lb Ellis washer, followed by a Colmac 2100-3 finishing tunnel, which can process 5,000 shirts per hour. The facility recycles its water for re-use during early stages of washing. In addition, the facility contains a heat reclamation system. This plant is one of the newer plants and uses state of the art equipment.

7.2.3 DISPOSAL (OR END-OF-LIFE)

At the end of a shirt's useful life, it is discarded in a landfill. A shirt is retired from service once it is no longer presentable for MLS's customer to wear. This decision is made by MLS and sometimes with input from its clients. MLS collects garments destined for the landfill at three locations: Sacramento, CA; Chino, CA; and Phoenix, AZ. This model assumes an average distance of 50 km to the nearest landfill for disposal.

7.3 ASSUMPTIONS AND LIMITATIONS

In performing any LCA, some assumptions are made in modeling the product system specifications (product composition, percentage of waste, life span, truck/boat utilization rate, etc.). This inevitably leads to some uncertainties in the results. For the shirt creation phase, this study primarily utilized data from a professional database or other LCA literature. Because these sources of data do not necessarily reflect the exact processes or inputs utilized by the client's shirt suppliers, there is potentially a higher degree of uncertainty in the results from that stage.

In the use phase, consistent processes were assumed for every load of laundry. However, in reality, there would be some amount of deviation from the modeled process used in this study. Although this study used some data derived from actual meter readings, other inputs came from specification sheets. One large uncertainty within the shirt use phase is in the water heating process due to the lack of MLS-specific data. The natural gas and water use and consumption information were obtained from specification sheets of similarly sized boilers, which represent machine operations under ideal conditions. Another source of uncertainty is within transportation at the Chino and Sacramento facilities. Mileage and the vehicle utilization ratio were only obtainable for the Oceanside and Santa Barbara facilities, so general assumptions had to be for this process for the Chino and Sacramento plants. Furthermore, since this study did not examine detergents and chemicals used in laundering the shirts, the energy and water inputs and its associated environmental impacts were also excluded.

Within the shirt disposal phase, uncertainty lies within the transportation process. This is because the actual distance from the point of disposal to the landfill is not known, so it was estimated. In addition, while the product being disposed of in this study is a polyester/cotton shirt, the data for operating and maintaining the landfill came from the GaBi database for general landfill operations in Switzerland that collects an assortment of wastes. The composition of organic matter that can break down and release methane may differ from the shirt. Furthermore landfill operations and maintenance practices may not be the same in the two countries as regulations may differ.

In addition to the assumptions described above, detailed calculations with corresponding assumptions are covered in **Appendix B: LCI Assumptions and Calculations.**

8. RESULTS

The results presented in this section show the life cycle energy use, global warming potential (GWP) and water use for the shirt's life cycle. The energy results are reported in megajoules (MJ). According to the Department of Energy, the average household uses about 109 MJ per day (US EIA, 2009). The GWP results are reported in kg CO_2-equivalent and represent the potential environmental impact from GHG emissions from the product system. A typical small car releases 0.47 kg CO_2-

equivalent per mile (US DOE, 2008). The total water used is reported as consumptive use and non-consumptive use to reflect the difference between the two types of water use. Consumptive water use is water that is permanently removed from a system via evaporation, transpiration or incorporation into a product (Torcellini et al. 2003). In contrast, non-consumptive water use describes water that is temporarily removed from a system, but is returned to its source and not substantially degraded in quality. Most hydropower generation uses water non-consumptively. Also typically, water that is treated sufficiently and returned as surface water after industrial processes are considered non-consumptive uses of water. In order to distinguish between the two types of water use, the model assumed that approximately 30% of the water used during the generation of electricity is consumed as a result of evaporative cooling in thermal power plants; approximately 10% of the water used in industrial and laundering machinery is consumed as a result of evaporation. Furthermore, approximately 70% of water required for the production of cotton is consumed as a result of evapotranspiration. Water use and consumption numbers are reported in liters (L). An analysis of the results is presented in the discussion section.

8.1 OVERALL LCA

The results from the LCA show that the creation, use and disposal of a 65% polyester/35% cotton shirt consumed a total of 102 MJ of energy (equivalent to burning 0.8 gallons of gasoline), contributed to a global warming potential of 5.7 kg CO$_2$-equivalent (the consequence of burning 1 gallon of propane), and non-consumptively used 2,276 L and consumed 452 L of water (roughly 15 average bathtubs). The use phase consumed the greatest amount of energy (64%), contributed the most to GWP (72%), and non-consumptively used the most water (82%) compared to the shirt creation and disposal phases. However the shirt creation phase consumptively used the most water (54%), largely due to water evapotranspiration during cotton production. The resource use and potential environmental impact from the shirt creation phase was slightly less than the use phase, while the shirt disposal phase only accounted for an insignificant amount of energy use, water use and contribution to GWP (See **Table 1** below).

Table 1 Overall LCA results

	Shirt Creation		Shirt Use/Laundry (Facility Average)		Shirt Disposal		Total
Energy (net calorific value) [MJ]	36.7	36%	65.3	64%	0.2	0.2%	102.3
EDIP 2003, Global warming [kg CO2-Equiv.]	1.5	27%	4.1	72%	0.1	1.5%	5.7
Total Water use (L)	644.73	24%	2083.7	76%	0.3	0.0%	2728.8
Non-consumptive (L)	400.27	18%	1875.3	82%	0.3	0.0%	2275.9
Consumptive (L)	244.46	54%	208.37	46%	0.0	0.0%	452.9

8.2 SHIRT CREATION PHASE

Results for energy use, GWP and non-consumptive and consumptive water use for the shirt creation phase are presented below.

Energy Use

The polyester production process accounted for the highest energy use (nearly 18 MJ) for creating a 65% polyester/35% cotton shirt. The next few energy intensive unit processes were yarn manufacturing and cotton production. The lowest energy use occurred in the finishing, pre-treatment and weaving processes. It should be noted that mass losses due to waste occurs in most steps of the shirt creation process, therefore, adding to the energy use of the earlier unit processes. The exact amounts of mass loss are specified in Appendix B. One surprising result from this LCI is that cotton production accounted for less than three times the energy required for producing polyester for the shirt (See **Figure 5** below).

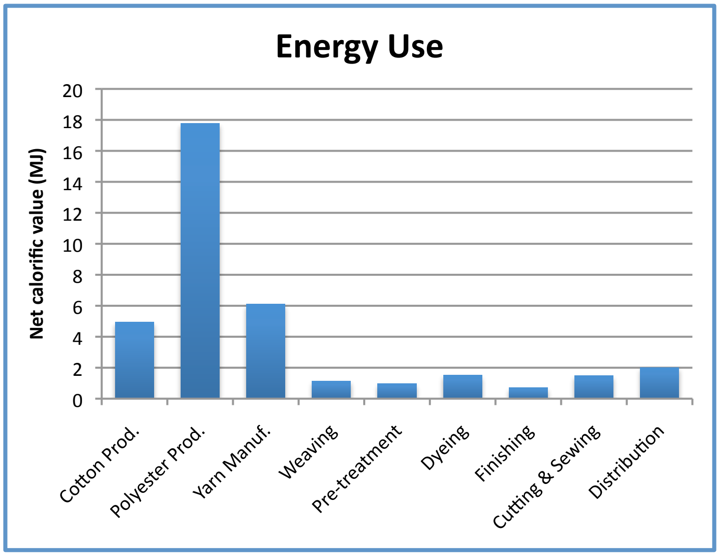

Figure 5 Energy use per shirt for each process in shirt creation phase.

Global Warming Potential

Because polyester production required the most energy of all unit processes, it also contributed the most to GWP with 0.6 kg CO_2-equivalent. The potential global warming impact was high due to the large amount of energy required to extract and refine crude oil to make polyester, in addition to the polyester production process itself. The yarn manufacturing process also required a lot of energy, and thus represents the next highest GWP at 0.3 kg CO_2-equivalent. The lowest GWP occurred in the finishing, weaving and pre-treatment processes, at 0.04 kg CO_2-equivalent, 0.058 kg CO_2-equivalent and 0.059 kg CO_2-equivalent, respectively. The global warming potential correlates closely with the amount of energy used for each unit process (See **Figure 6**).

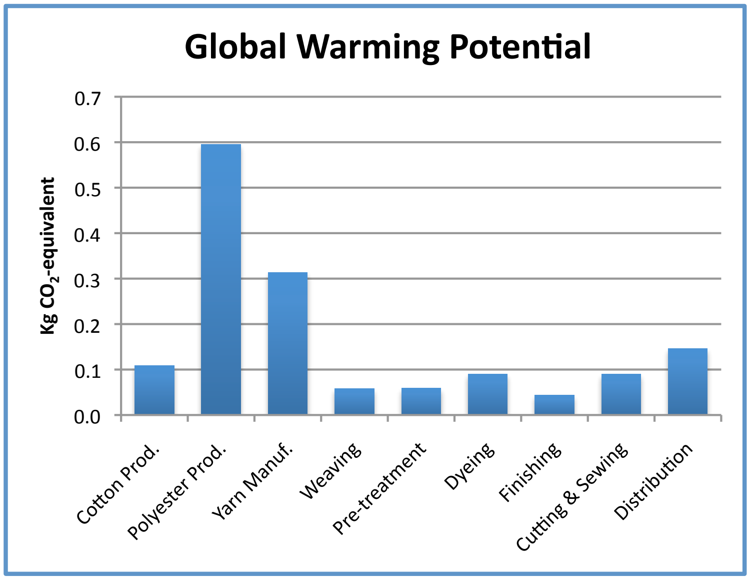

Figure 6 Global warming potential (GWP) per shirt by process for shirt creation phase

Non-Consumptive and Consumptive Water Use

The largest total use of water occurred within the cotton production process, which non-consumptively used 90 L and consumed 210 L of water. It should be noted that water requirements for cotton cultivation in the US are significantly lower compared to the world average (EDIPTEX, 2007). The large difference in cotton cultivation water requirement depends on whether the crop is irrigated or relies on rainfall. The yarn manufacturing process had the second largest total water use, mostly due to the utilization of electricity to operate the machinery, as the process non-consumptively used 205 L and consumed 23 L. The weaving process non-consumptively used the next largest amount of water at 43 L, followed by the cutting and sewing process at 21 L. Finishing and distribution of shirts required the least amount of water within this phase (See **Figure 7** below.)

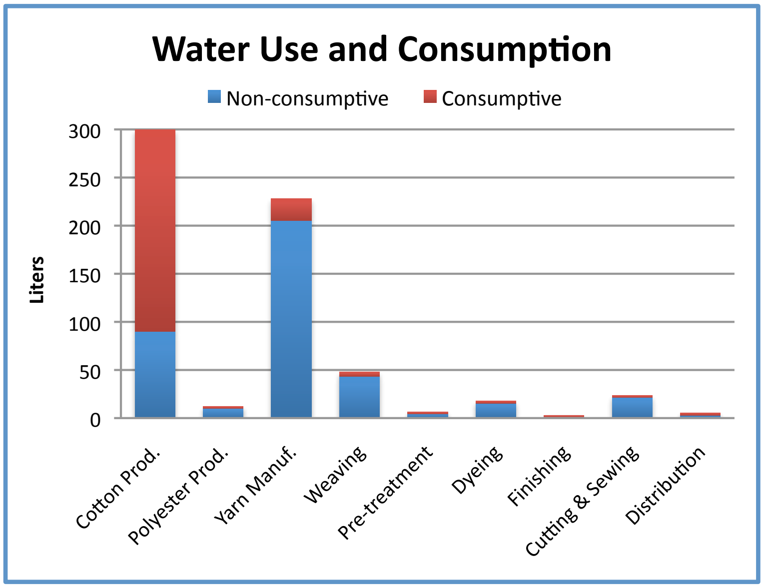

Figure 7 Non-consumptive and consumptive water use per shirt by process for the shirt creation phase

Table 2 Results from the shirt creation phase

	Cotton Production	Polyester Production	Yarn Manufacturing	Weaving	Pre-treatment	Dyeing	Finishing	Cutting & Sewing	Shirt Distribution
Energy (net calorific value) [MJ]	4.94	17.8	6.1	1.1	0.98	1.5	0.72	1.5	2
EDIP 2003, Global warming [kg CO_2-Equiv.]	0.1	0.6	0.3	0.06	0.06	0.09	0.04	0.09	0.15
Total Water use (L)	299.98	12.2	228.2	48.2	6.4	17.7	3	23.7	5.3
Water use (L)	90	11	205.4	43.4	5.8	15.9	2.7	21.3	4.8
Water consumption (L)	209.99	1.2	22.8	4.8	0.64	1.8	0.3	2.4	0.53

8.3 SHIRT USE PHASE

The results for the shirt use (laundering) phase are separated into two sections. The first section describes the average resource use and environmental impacts for MLS's operations for each of the four facilities and the facility average. In the second section, the same information is illustrated but broken down by process (i.e. water heating, washing, etc.)

The results reported in each section present energy use, GWP, non-consumptive water use and consumptive water use, assuming that one shirt is laundered throughout its entire life (52 washes) at just one of the MLS facilities. The graphs illustrate which facilities and individual processes contribute the most to each resource and impact category.

8.3.1 SECTION I: RESOURCE USE AND ENVIRONMENTAL IMPACT (FACILITY AVERAGE AND INDIVIDUAL PLANTS)

Energy Use

The facility average energy consumption in the use phase was approximately 65 MJ. By facility, the results show that the Chino and Santa Barbara plants used the largest amount of energy for 52 laundering cycles at approximately 75 MJ and 73 MJ, respectively. The Sacramento facility used roughly 61 MJ of energy and the Oceanside plant consumed about 42 MJ (See **Figure 8**).

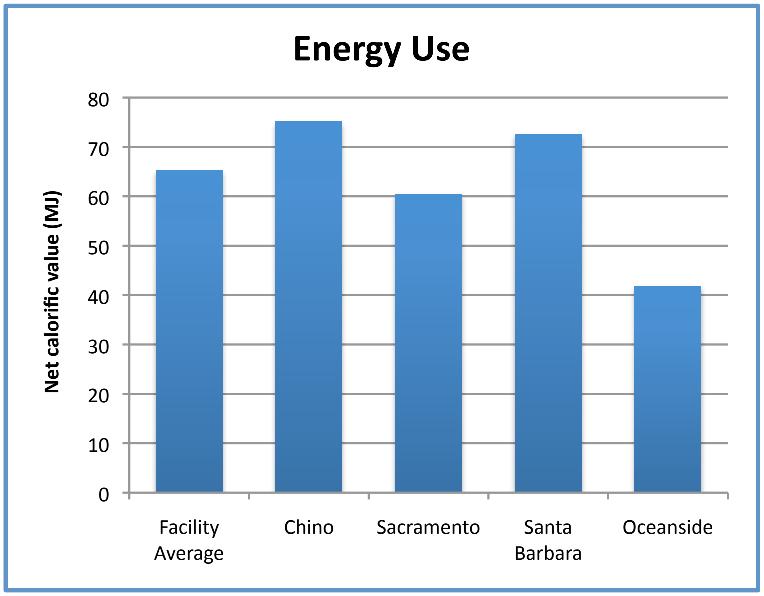

Figure 8 Energy use per shirt for the use phase MLS facilities average and at each of the four plants

Global Warming Potential

The facility average contribution to global warming potential was just over 4 kg CO_2-equivalent. Among the MLS facilities, the Chino facility had the highest global warming potential per shirt at 4.6 kg CO_2-equivalent, followed by the Santa Barbara facility at 4.4 kg CO_2-equivalent, the Sacramento facility at 3.8 kg CO_2-equivalent and the Oceanside facility at 2.7 kg CO_2-equivalent (See **Figure 9**).

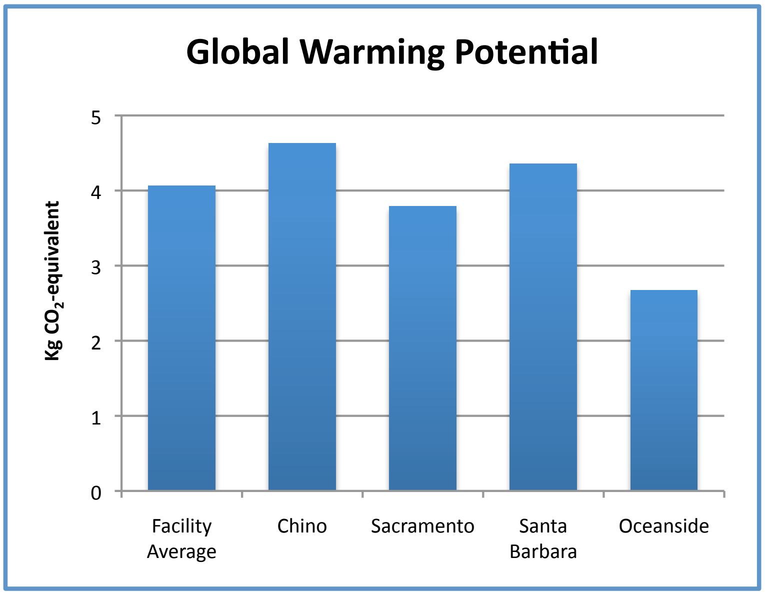

Figure 9 Global warming potential per shirt for MLS facilities average and at each of the four plants

Water Use and Consumption

The average facility non-consumptive water use and consumptive use was 1,875 L and 208 L for the entire use phase or 36 L (9.5 gallons) non-consumptively used and 4 L (1 gallon) consumed during an average laundering session. The Santa Barbara and Chino facilities non-consumptively used and consumed the most water, whereas the Sacramento and Oceanside plants required the least amount of water (See **Figure 10** below).

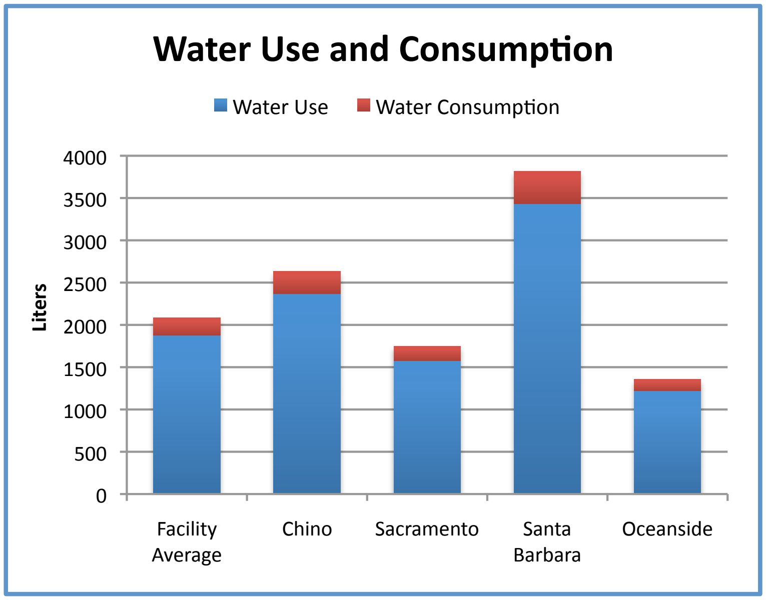

Figure 10 Non-consumptive and consumptive water use per shirt for the use phase, MLS facilities average and at four facilities

Table 3 Results from the use phase

	Facility Average	Chino	Sacramento	Santa Barbara	Oceanside
Energy (net calorific value) [MJ]	65.3	75.1	60.5	72.6	41.9
EDIP 2003, Global warming [kg CO_2-Equiv.]	4.1	4.6	3.8	4.4	2.7
Total Water use (L)	2083.7	2633.7	1748.6	3815.7	1355.8
Water Use (L)	1875.3	2370.4	1573.7	3434.2	1220.2
Water Consumption (L)	208.4	263.4	174.9	381.6	135.6

8.3.2 SECTION II: RESOURCE USE AND ENVIRONMENTAL IMPACT (FACILITY AVERAGE AND INDIVIDUAL PLANTS) BY PROCESS

Going one step beyond the results in the last section, the following graphs assist in the identification of resource use and environmental impact hot spots by process within each plant.

Energy Use

The process that consumed the most energy on a facility-average level was the drying step. This step also includes pressing and finishing, depending on the method of drying process at each facility. Water heating, washing and distribution of the shirts used nearly an equal amount of energy, closely following the consumption for the drying process. The results from this graph show that each plant achieves different efficiencies for each separate process. Oceanside, being one of MLS's newest facilities, used the least amount of energy for the on-site industrial processes. However, traveling greater distances to deliver the shirts increased the energy use from shirt distribution and collection to its clients (See **Figure 11** below).

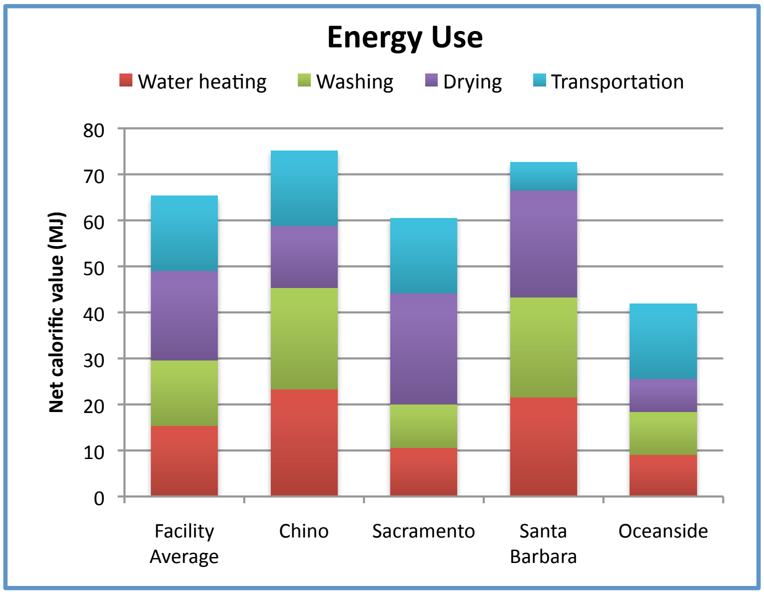

Figure 11 Energy use per shirt for MLS facility average at each of the four plants, by process

Table 4 Energy use per shirt for MLS facility average at each of the four plants, by process

Energy (net calorific value) [MJ]	Facility Average	Chino	Sacramento	Santa Barbara	Oceanside
Water heating	15.3	23.3	10.6	21.6	9.1
Washing	14.3	22.0	9.5	21.6	9.3
Drying	19.5	13.5	24.1	23.3	7.2
Transportation	16.2	16.3	16.3	6.1	16.3
Total	65.3	75.2	60.5	72.6	41.9

Global Warming Potential

The GWP results correlate closely with the amount of energy used by each facility. The use phase GWP is highest in the Chino and Santa Barbara plants and lowest in Oceanside. The breakdown of GWP by process closely mimics the energy use results (See **Figure 12** below).

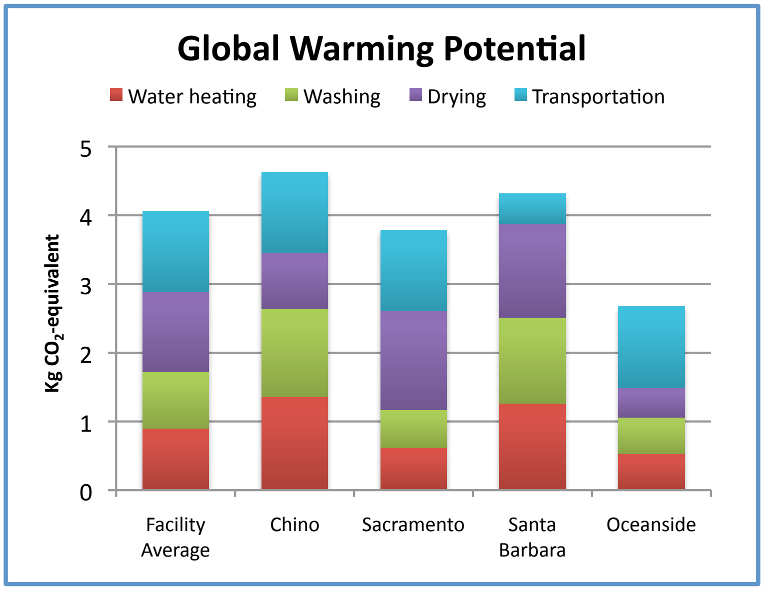

Figure 12 Global warming potential per shirt for MLS facility average at each of the four plants, by process

Table 5 Global warming potential per shirt during the use phase for MLS facility average at each of the four plants, by process

EDIP 2003, Global warming [kg CO_2-Equiv.]	Facility Average	Chino	Sacramento	Santa Barbara	Oceanside
Water heating	0.9	1.4	0.6	1.3	0.5
Washing	0.8	1.3	0.6	1.3	0.5
Drying	1.2	0.8	1.4	1.4	0.4
Transportation	1.2	1.2	1.2	0.4	1.2
Total	4.1	4.6	3.8	4.3	2.7

Non-Consumptive and Consumptive Water Use

Water consumption is represented in Figure 13 as an aggregate of water consumed by each process, and represents the evaporative loss during electricity generation. Non-consumptive water used was mostly equal across the water heating, washing and drying processes by facility average. The greatest amount of water non-consumptively used and consumed by facility process occurs at the Santa Barbara facility, followed by the plant in Chino. Again the Oceanside facility operated the most efficiently in terms of total water use. In examining how water is utilized, the non-consumptive water use is significantly greater than the consumption of water at all of the plants (See **Figure 13** below).

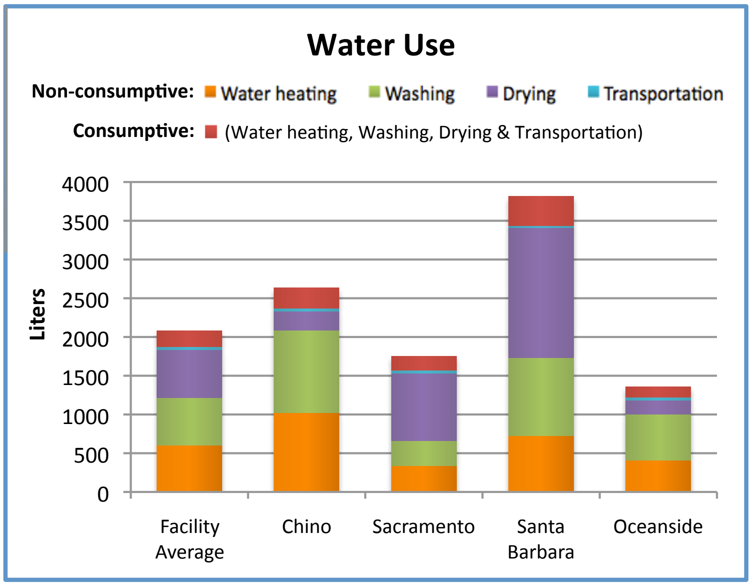

Figure 13 Non-consumptive and consumptive water use per shirt at each of the four MLS facilities, by process

Table 6 Non-consumptive and consumptive water use per shirt at each of the four MLS facilities, by process

Water Consumption and Use (L)	Facility Average		Chino		Sacramento		Santa Barbara		Oceanside	
	Use	Consumption	Use	Consumption	Use	Consumption	Use	Consumption	Use	Consumption
Water heating	601.9	66.9	1024.3	113.8	341.3	37.9	728.3	80.9	406.6	45.2
Washing	613.1	68.1	1062.6	118.1	318.1	35.3	1003.5	111.5	594.2	66.0
Drying	622.0	69.1	245.0	27.2	875.8	97.3	1688.1	187.6	181.0	20.1
Transportation	38.2	4.2	38.4	4.3	38.5	4.3	14.3	1.6	38.5	4.3
Total	1875.3	208.4	2370.4	263.4	1573.7	174.9	3434.2	381.6	1220.2	135.6

9. DISCUSSION

The following sections include an interpretation of the overall LCA results and by phase (shirt use, creation, and end-of-life), along with a discussion of model uncertainties.

9.1 INTERPRETATION OF RESULTS

The life cycle inventory and assessment for this study indicate that the shirt use phase used more energy, used more water non-consumptively, and contributed more to the global warming potential than the shirt creation or disposal phases (Table 1). These results are consistent with previous garment LCA studies, which concluded that the use phase of a garment's life cycle uses the largest amount of resources and are responsible for the greatest amount of potential environmental impact (Bass, *et al.*, 2010 and Farrant, 2008).

Water-energy nexus

A common theme from the overall results of this LCA and an important conclusion emerging from literature is that energy production can be very water-intensive, depending upon the energy source and method of production (California Energy Commission, 2006). Additionally, water use can be quite energy-intensive (Baum and Chaisson, 2003; Cohen et. al., 2004). In California this includes energy required for pumping, conveyance and treatment of water. Therefore, the use and consumption of water resulting from each process reflects not only the water used directly, but also the amount of water used and consumed in the production of energy used in that process. The production of electricity in particular uses and consumes large amounts of water compared to natural gas production. This is because water is required in various applications to generate electricity and consumed via evaporative cooling at power plants. Natural gas production and combustion have a lower contribution to GWP per MJ compared to electricity and requires less water for production (US DOE 2008, CEC 2006). Certain energy sources are also more efficient per kWh, for example hard coal produces 27 MJ per kWh and natural gas produces 44 MJ per kWh (Kuczenski 2010). The ratio of natural gas to electricity used by each process influences the resulting magnitude of GWP and water use.

9.1.1 SHIRT CREATION PHASE

In the shirt creation phase the largest use of energy occurred during the production of polyester fibers, manufacturing of yarn and the cotton production process. The production of polyester fibers relies heavily on the use of fossil fuels. Consequently, it is also the largest contributor to global warming potential in the shirt creation phase. It also consumes a significant amount of energy from the use of crude oil, natural gas and electricity for polyester production. However the manufacturing of polyester requires very little amounts of water. It should be noted that the polyester content of the shirt is almost twice the amount of cotton, so polyester contributes to even greater environmental impact due to the weight-based allocation method. The yarn manufacturing process uses large amounts of electricity to power machines. Thus, the yarn making process is the next highest contributor to GWP after the production of polyester fibers.

The resource use and environmental impacts from transportation consumed the least amount of resources in the shirt creation phase, despite the fact that the shirt assembly involves international transport. This is a result of the economies of scale in ocean and heavy tractor-trailer truck transportation.

Not surprisingly, cotton production has a relatively large water requirement since it is generally known as a water-intensive crop. Due to the large evapotranspiration losses, a large percent of the water is consumed. The US cotton cultivation process is significantly more water efficient that the world average, a general result of agricultural practices in developed countries. In addition, some areas of the US require significantly less irrigation due to availability of rainwater. Since the exact source of cotton is unknown, a US average was necessary.

9.1.2 SHIRT USE PHASE

In the shirt use phase, both Chino and Santa Barbara facilities show the highest energy use and global warming potential of all four facilities (Figures 5 and 6). At both plants, the high energy use and resulting high global warming impact are principally due to the large amounts of energy used in the water heating and drying processes. The distance covered for shirt distribution in Santa Barbara is shorter than the distances covered in Chino, Oceanside and Sacramento thereby contributing to the differences in energy use for transportation.

In contrast, the Sacramento and Oceanside facilities consume approximately half of the energy during the water heating and washing processes than do the other two plants. This is primarily because the Sacramento and Oceanside facilities utilize more efficient boiler and washer processes than do the Chino and Santa Barbara facilities. At the Sacramento and Santa Barbara plants, the greatest amount of energy consumption takes place during the drying process because they employ the use of an electric-powered Triple Buck press. The Oceanside facility is by far the most energy efficient of the four facilities, utilizing relatively higher efficiency boiler and washer processes, as well as an efficient natural gas powered laundering tunnel in the dryer process.

The largest amount of water non-consumptively used and consumed out of all four facilities occurs at the Chino and Santa Barbara facilities. This is due primarily to the large amount of water that is embedded in the relatively higher amount of energy used at those facilities. The production of electricity in particular uses and consumes large amounts of water. This is because water is used in various applications to generate electricity, as well as consumed via evaporative cooling at power plants. This is reflected in the large volumes of water used in the dryer process, which include electric Triple Buck presses utilized at both the Santa Barbara and Sacramento facilities. The amount of water consumed in the dryer process at the Sacramento facility is roughly half that of the Santa Barbara facility because 50% of the shirts go through a more efficient natural gas powered laundering tunnel. The Oceanside facility uses and consumes the least amount of water, largely due to the newer, more energy efficient equipment used at the facility.

9.1.3 END-OF-LIFE PHASE

The energy consumed during the shirt disposal, or EoL, phase mainly comes from the transportation of the used garment to the landfill facility, as well as the operations and maintenance of the landfill. Consequently, the energy and water use and GWP associated with the Eol phase are due primarily to the energy used to transport the garments to the landfill, as well as the operation and maintenance of the landfill. The shirts in the landfill contribute relatively little environmental impact as polyester is largely inert. In the laundering process, cotton slowly disintegrates so the shirt gradually loses its cotton content. Although there is some cotton remaining at end of the shirt's life, the amount of cotton remaining in the shirts is significantly reduced. The contribution to methane emissions in the breakdown process in the landfill is small.

9.2 SENSITIVITY ANALYSIS

To assess the robustness of the LCA results, a sensitivity analysis is performed to identify key parameters that have the greatest influence on the outcomes of the study. In the sensitivity analysis, variations in process data, choice of assumptions, and other variables are changed to determine how the choices affect the LCI and LCIA results. In this study, a standard deviation of +/- 50% is applied to parameters in those unit processes with high resource use and environmental impact in the shirt creation and laundering phases. Utilizing the sensitivity analysis function in GaBi, a percentage change in the energy use (net calorific value), water use and global warming potential is calculated for the parameters being examined. Key findings are presented in **Appendix C**.

Overall life cycle

In the overall life cycle of the shirt, increasing and decreasing the number of times a shirt is worn and laundered over its lifespan resulted in the greatest change, close to +/-19% in energy use, GWP and water use (Appendix C, Table 1).

Shirt creation phase

In the shirt creation phase, the percentage of waste assumed in the model for yarn manufacturing is a source of uncertainty. Altering the percentage of waste, hence impacting the amount of cotton and polyester materials needed to produce the amount of yarn necessary to manufacture enough fabric for the shirt, does in fact result in the largest impacts (Appendix C, Table 2). This analysis shows that more accurate percentages of waste loss for cotton and polyester would be needed. A sensitivity analysis is also performed for the transportation of products between processes in the shirt creation phase. Despite the occasional long distances needed to ship the intermediate products between processes, the energy and water use and GWP does not change significantly when inputs are adjusted up and down by 50% (Appendix C, Table 3). This is because the total weight of the trucks and boats that are transporting goods are scaled down to the resources necessary to transport one shirt.

Shirt use phase

For the shirt use phase, parameters for several processes are examined for output sensitivity. An analysis is run for the Chino and Sacramento facilities only since those two facilities launder over 90% of the shirts modeled in our study. Starting with the water heating process in the Chino plant (Appendix C, Table 4), the

GWP resulting from the steam produced by the boiler is moderately sensitive to a 50% increase and decrease in the inputs. An increase in the production of steam signifies a more efficient boiler, hence decreasing the GWP resulting from the life cycle use of hot water. This inverse relationship holds true when the steam production is decreased, resulting in a higher GWP.

For the washing process, this study models the inputs from MLS's washing formulas. The actual amounts of water and energy used by the facility is measured and documented by the client, therefore, there is very little uncertainty in the data used for this unit process. However, a sensitivity analysis is still performed to determine how increases or decreases in the efficiency of the washers affect the energy use, GWP and water use for the life cycle use in that process. The analysis shows that the total weight of shirts for each load and the amount of water, especially hot water, used are moderately to highly sensitive parameters.

In the Chino plant, the shirt drying process is done in tunnel. For that process, the GWP results from the tunnel capacity parameter, or the number of shirts that can be fed into that equipment for drying, is the most sensitive to changes in the inputs.

The results of the sensitivity analysis performed for the Sacramento plant is similar those of the Chino facility (Appendix C, Table 5). A sensitivity analysis is not done for shirt disposal since the impacts from that phase is under 1.5% of the total life cycle of the shirt.

10. VALIDATION

One way to verify the results from this LCA is to perform cross checking with the results obtained from a different LCA approach. While this LCA utilizes the process-based LCA approach by itemizing inputs and outputs for each unit process, the economic input-output (EIO) LCA method analyzes and quantifies the life cycle environmental impacts of each unit of output of products and services in each sector in the economy. An EIO model is a matrix that links the economic value of outputs from a sector (listed in rows) with inputs into another sector (listed in columns) of an entire economy. With this method, the entire supply chain is captured when evaluating a specific sector. By adding environmental impacts to the matrix, the EIO model evaluates the environmental impacts associated with each unit of output for each sector (Carnegie Mellon University Green Design Institute).

The Comprehensive Environmental Data Archive 4 (CEDA 4) is a robust EIO LCA software tool used by professional LCA practitioners. This software utilizes publically available US economic and environmental flow data from year 2002 of over 400 US commodities and services categorized by the North American Industry Classification system (NAICS) code (Suh, 2010a). By entering the consumer's price for a specific sector, CEDA can quantify the environmental impacts of the products or services of that sector throughout the US economy. The resulting data is classified by climate change category and characterized using the GWP indices published by the IPCC for a 100-yr. baseline to obtain global warming potential reported in kg CO_2-equivalent. CEDA also models and reports water withdrawal quantities using USDA data from 2000 and 2005, but interpreted for 2002.

To compare the LCA results of this study with the results from CEDA 4, the 2002 consumer price for each LCA phase needs to be determined. **Appendix D** shows the calculations for obtaining the consumer prices (Suh, 2010b). The results are shown in **Table 8** below.

Table 8 Comparison of LCA results from this study with CEDA results

	GWP (kg CO2-equiv.)	Total water use (liters)
Shirt Creation		
This LCA	1.5	645.0
CEDA 4	4.5	674.4
Use		
This LCA	4.1	2083.7
CEDA 4	5.2	571.3
Disposal		
This LCA	0.1	0.3
CEDA 4	0.5	4.8

The purpose of this validation exercise is to determine if the outcomes of this LCA study come within the same order of magnitude of those generated by CEDA. In fact, the results from this study compared relatively closely with those from CEDA. It should be noted that because CEDA examines aggregated processes for each industrial sector, it cannot produce precise results for a specific process. For example, in the shirt use phase, the services categorized in CEDA are not only for linen and uniform supply, but also for dry-cleaning services. Since dry-cleaning mainly uses solvents instead of water to clean fabrics, it can explain the lower amount of total water use derived from CEDA for the laundering phase.

11. CONCLUSIONS AND RECOMMENDATIONS

The following sections address report conclusions and recommendations for MLS. Recommendations are filtered into two categories: those identified more specifically from LCA results and those founded more broadly on literature review. The latter category is included to more fully address the goals of MLS in commissioning this project and is therefore supplementary to the chief LCA recommendations.

11.1 CONCLUSIONS

The results of this LCA create a resource use and an environmental impact baseline for at 65% polyester/35% cotton shirt laundered fifty-two times at MLS. The total life cycle energy use of the shirt is 102 MJ (equivalent to burning 0.8 gallons of gasoline), cumulative water use is 2,729 liters—2,276 liters of non-consumptive use and 453 liters of consumptive use—(or roughly 15 average bathtubs), and contribution to global warming is 5.7 kg CO_2-equivalent (or the consequence of burning 1 gallon of propane).

Of the three distinct phases, the amount of resources used and contribution to global warming is the highest in the shirt's use phase, accounting for 64% of energy use, 72% of water use, and 76% of the global warming potential. These results are consistent with previous apparel LCAs that have reported the shirt use phase as having a higher environmental impact than the shirt creation phase. In the shirt use phase, all four processes consume similar amounts of energy and are responsible for nearly equal global warming potential on a facilities average level. The total water requirement, however, is relatively balanced between water heating, washing and drying, but much lower for distribution of the shirts. The resource use and environmental impact of each process within each plant varies significantly. For example in Santa Barbara and Sacramento, the hot spot is the drying process but in Chino the hot spots are in the water heating and washing processes. Oceanside, being equipped with newer equipment, consumes fewer resources.

The shirt creation phase accounts for 36% of the energy use, 27% of total water use, and 24% of the global warming potential. Polyester production and yarn manufacturing consume the highest amount of energy, while cotton cultivation and production requires the most water.

Disposing of the shirt contributes less than 1.5% in the three impact categories examined above.

One common theme in the LCA results is the relationship between energy and water use. Energy and water go hand-in-hand, as energy production involves intense water use—for activities like pumping crude oil, generating steam that turns turbines, and keeping power plants cool. Conversely, treating and transporting water requires intense energy use. It should be noted that processes that are energy intensive also resulted in higher water usage, since all upstream resource use is taken into account in this LCA.

The recommendations for this study focus mainly on improving the processes for the hot spots, or areas that use the most energy and water and contributes the greatest to global warming and are presented in the next section.

11.2 RECOMMENDATIONS

11.2.1 LCA IDENTIFIED RECOMMENDATIONS

11.2.1.1 SHIRT CREATION PHASE

The LCA results highlight the water and energy-intensive nature of garment creation, a concept not new to life cycle thinking in the textile industry. Making changes to the upstream process (pre-MLS) of shirt creation will be challenging for a laundering company like MLS as it will require collaboration of a number of suppliers working towards a common goal. However, if MLS decides to engage suppliers on sustainability issues, this study will help MLS target their efforts towards the process with the highest environmental impacts.

Polyester production

Polyester fiber production accounted for the highest energy use and contribution to global warming in the shirt creation phase. One way to reduce the resource use and environmental impacts of producing a 65% polyester/35% cotton shirt is to utilize recycled polyester (Patagonia, n.d.) According to a white paper produced by the outdoor clothing company, Patagonia, using recycled polyester achieves a net energy use and global warming reduction in the entire life cycle of a garment, despite transporting discarded polyester and finished recycled polyester fibers between Asia and the U.S. Recycling garments also diverts materials from the precious space in the remaining landfills in the U.S. Their Common Threads Initiative program has the ultimate goal to close the loop in the product life cycle, replacing virgin materials with recycled ones. With the technology and feasibility already in place, MLS can work with their shirt supplier to identify sources of recycled polyester fibers that can be incorporated into their garments. Cintas, one of MLS's competitors, has already begun offering uniforms that use 50% recycled polyester derived from plastic bottles. They cite that hotel companies have requested products that are made more sustainability from their uniform rental suppliers (Rosselli, 2008).

Cotton production

Although cotton production is not as energy intensive as polyester, the cultivation and harvesting of the crop can be water intensive. One solution to reducing the water use of cotton production is to switch to organic cotton. Cotton produced from organic-growing practices is typically less water-intensive than conventional methods (Chouinard & Brown, 2008). As an alternative to organic cotton, MLS could also switch to a cotton supplier that is recognized as providing sustainably-grown cotton, but not quite to the extent of organic-certified. Organic cotton sometimes poses difficulties to sourcing activities in terms of quality, supply, and upfront cost; thus, investigating alternative sustainably cultivated cotton could help MLS insulate from associated supply chain upsets. Such options include purchasing all cotton from a "Better Cotton Initiative" (BCI) or "Sustainable Cotton Project" (SCP) supplier.

BCI is an international organization whose focus is to educate farmers on cotton growing practices that are least water and chemical intensive. Furthermore, BCI assists in matching large-scale cotton consumers with BCI approved suppliers to make purchases while minimizing additional costs (BCI, 2009). Many large clothing retailers, including Adidas and Marks and Spencer have supported BCI initiatives.

SCP, on the other hand, is a California based company that educates cotton growers on bio-intensive integrated pest management in order to reduce harmful chemical use in cotton cultivation and produce what they call "Cleaner Cotton" (SCP, 2011). Similar to BCI, SCP also works at various levels of the supply chain in order to link Cleaner Cotton growers to Cleaner Cotton manufacturers and retailers (SCP, 2011). Further investigating either of these options for cotton sourcing could assist MLS in locating a sustainable cotton supplier while minimizing upfront costs on the company.

11.2.1.2 SHIRT LAUNDERING (USE) PHASE

One of the more challenging aspects of creating an LCA is accurately modeling the process that the LCA is designed to address. In conducting this LCA, raw data collection at the MLS-facility level was hindered by the fact that not all equipment was outfitted with energy or water monitoring meters. Thus, should MLS choose to put further resources towards improvements in life cycle impacts, installation of energy and water meters on the equipment to be studied is recommended. Metering activities can help provide a baseline for performance to identify inefficient operation, down to specific machines. Such specificity is not engendered through lump sum measurements. For example, the shirt LCA identified that dryers and boilers consume significant energy amounts at most facilities. Metering would allow comparison to equipment specification sheets, which could help identify if the machines are in need of repairs or replacements.

The study indicates that the Santa Barbara and Chino laundering facilities have the most intensive use of energy and water per shirt among the four facilities assessed. This owes largely to the facilities' less efficient electric-powered equipment used in some of the laundering processes. Equipment upgrades to ones that are more energy efficient, especially those relying most on natural gas, could obtain substantial savings in energy and water use. A cost benefit analysis would be necessary to determine the economic feasibility of this option.

Representing a large proportion of total energy use in the laundering phase, boilers also represent opportunities for large energy savings. This study assumed all boilers operate at 100% efficiency, in accordance with the equipment specification sheets. In reality, it is more likely that the boilers efficiencies are about 15-20% less than optimal due to their age and required maintenance (Council of Industrial Boiler Owners, 2003). Measures including boiler insulation, heat loss recovery, optimizing start-up conditions, and preheating combustion air can all significantly increase boiler operating efficiency (Jayamaha, 2007). Thus, by monitoring and maintaining boilers to ensure they are operating at maximum efficiency, MLS could achieve significant energy and cost savings.

At the time of this report publishing, the authors identified an industry trend toward more cutting-edge technologies to advance environmental performance. Examples include alternative water efficiency measures and substitute solvents, which can provide cost-effective and environmentally friendly solutions on an industry scale. Supercritical carbon dioxide-based laundry systems have the potential to significantly decrease water and energy usage by eliminating the need for dryers. In an effort to demonstrate the technical and economic feasibility of this technology, the California Energy Commission recently awarded CO2Nexus with funds for a project that will compare cost, operation, and water and energy consumption between the carbon dioxide cleaning and water-based cleaning machines (California Energy Commission, 2010). It is recommended MLS follow the progress and results of this study and stay abreast of grant opportunities for similar research participation.

Solar water heating

As energy use for water heating represents a significant amount of the total energy use in laundering, one measure for improvement is the installation of solar water heating systems at MLS's laundry facilities. This system not only helps MLS reduce its energy use, but it can also reduce water use in the laundry phase. As much water is embedded in electricity generation, this solution also represents significant savings where solar water heaters are replacing electricity-powered boilers.

Solar water heating systems have shown to reduce energy consumption by as much as 80% and in the US alone, over one million residential and 200,000 commercial solar water heating systems have been installed (NREL, 1996). The technology is rather straightforward. The sun heats the surface of the solar collector and the heat is transferred either directly to potable water (direct active system) or to a heat transfer fluid (indirect active system) that eventually raises the temperature of the water to be stored in a tank until needed. There are also different types of collectors—low-, medium-, or high-temperature. High-temperature evacuated-tube collectors that can heat water/steam up to 177 degrees C can be suitable for large industrial facilities such as laundries (NREL, 1996).

To illustrate the potential benefits of this technology for a large facility, the Prince Kuhio Federal Building in Honolulu, Hawaii had installed a hybrid chiller heat recovery/solar water heating to supply a portion of the 10,600 L of hot water used in the building daily. By installing 71 square meters of flat-plate solar collectors on its roof, the solar component alone provided approximately 55% of the building's need for water heating. A financial analysis showed that the hybrid system had an initial installation cost of $58,389, with a net present value of the life cycle costs at $83,800 in 1997. The project has a calculated simple payback period of 9 years and an adjusted internal rate of return of 6.75% (NREL, 1997).

Considering MLS operates most of its laundering facilities in sunny locations with high insolation levels and the plants require high daily volumes of hot water use, mainly during the day, MLS can seriously consider the installation of solar water heating systems. To complete an economic feasibility analysis of this type of project, MLS can utilize the free Federal Renewable Energy Screening Assistant (FREScA) software package, available from the Federal Renewables Program at the National Renewable Energy Laboratory (NREL, 2011). Another useful resource is the free RETScreen Clean Energy Project Analysis Software developed by Natural Resources Canada (NRC, 2010). If initial capital investment is a deterrent to utilizing this technology, it should be noted that the California Solar Initiative-Thermal Program offers cash rebates of up to $500,000 for the installation of qualifying solar water heating systems for owners of businesses and industrial facilities (CPUC, 2011). Federal tax credits are also available for commercial buildings from the Energy Star program (US DOE and US EPA, 2009).

Transportation

Transportation was identified as another major source of environmental impact at MLS's facilities, particularly those facilities that service a large geographical area. It is recommended that MLS continue efforts to replace diesel and gasoline powered delivery vehicles with alternative fuel vehicles that provide a proven lesser life cycle environmental impact. The U.S. Department of energy operates incentive programs to transition vehicle fleets to more sustainable options (US DOE, 2011). MLS is encouraged to visit the government department's website for the most up-to-date incentive information and vehicle and fuel recommendations. Additionally, optimizing delivery routes and ensuring that all delivery vehicles are loaded to their maximum efficiency would help to reduce the number of unnecessary miles traveled, reducing resource consumption during the transport of laundered garments.

11.2.1.3 END OF LIFE PHASE

While end-of-life (shirt disposal) process rank low on the overall environmental impact scale of the LCA, relative to creation and laundering phases, MLS expressed interest in alternative shirt disposal options, to avoid landfill space and fees, and enhance the company's environmentally conscious image.

Currently, MLS garments are disposed of in a landfill when they can no longer be used. The wear lifespan of a 65% polyester/35% cotton shirt is typically about two years. MLS estimates that the company discards 3,175 to 3628 kg (or 7,000 to 8,000 lbs) 65% polyester/35% cotton shirts per year and spends approximately $2,000 annually on landfill delivery and disposal costs. Although this study found that the process of dumping retired shirts contributes little to resource use and greenhouse gas emissions when compared with contributions from the shirt creation and use phases, alternative shirt disposal options should continue to be explored. Landfill disposal fails to alleviate the need for new shirts and virgin materials. Recycling or reuse alternatives could reduce the amount of raw materials needed for production and also the amount of landfill space that MLS requires. From a strict cost perspective, MLS should consider that as the amount of available landfill space in California and other states decreases, associated fees might rise.

Shirts made of a blend of polyester and cotton fibers pose a problem for recycling feasibility (Hawley, 2006). Although processes to separate polyester from other fabrics are in development, they are not yet readily available on the commercial scale (Ouchi, 2009). The cost of separating the two textiles for recycling purposes is greater than the cost of creating virgin materials and the chemical-heavy separation process would also carry a sizeable environmental impact (Thiele). Without separation, however, the material may be down-cycled into insulation materials (Wang, 2010).

Presently, the costs necessary to disassemble shirts and transport parts to a recycling facility would exceed the cost of the dumping and landfilling shirts. Going forward, MLS should consider tracking the amount/number of garments disposed of in order to determine whether landfill alternatives such as textile recycling or scrap reuse might be practical options as landfill will likely increase (Farrant, 2008).

It is recommended that MLS consider extending the life of shirts by repurposing some shirts into reusable fabric tote bags or other items. However, while this would provide MLS with a marketing tool and outlet to recycle a portion of the used shirts, the labor and production costs would likely exceed those required for dumpster disposal.

11.2.2 BROADER RECOMMENDATIONS

11.2.2.1 BUSINESS STRUCTURE

Mission Linen Supply has engaged a number of environmental efforts to date and while this highlights a generalized trend toward corporate sustainability, these initiatives could gain greater traction through increased centralized authority to this end. To harness these "floating" initiatives so that they are traceable up the top of a corporate social responsibility (CSR) "umbrella," MLS can consider employing a stronger framework to support their responsibility system. Waddock and Bodwell's theory of Total Responsibility Management call for a "systemic, holistic, and process-oriented" framework if responsibility is to be effectively woven into the existing structure of an organization (Waddock et al., 2002). Ensuring a sustainability management role holds a recognized seat on the executive board or other governing body, could demonstrate company support for environmental initiatives and give sustainability initiatives adequate traction with company employees. To really integrate environmental strategy into the inner workings MLS, all levels of employees should have a level of accountability for working towards sustainability performance goals. A clearly structured chain of command throughout the company is necessary to support disseminated responsibility for achieving measurable goals, including environmental performance goals.

There are attractive environmental initiatives in various industries whereby, companies strategically promote their commitment to CSR once a substantive and credible CSR program is established. A commonly observed practice is corporations being a 'strong public champion' for environmental causes. However, this advanced step could invite public scrutiny if a strong formalized structure to support its CSR missions has not been strongly established (Freeman, 2006).

Partnerships with other bodies like industry peers, non-governmental organizations, and governments could also benefit MLS and be a good way to bring its commitment public. As MLS delves deeper into some of the issues surrounding CSR structural reorganization, it may be helpful to engage more experienced bodies. For example, when Wal-Mart sought a better understanding of the life cycle impacts of their products, they drew upon the expertise of Conservation International and Environmental Defense. Though this Bren group project is a first step to understanding MLS's life cycle impacts, the resources and time available are admittedly limited. Thus, it is recommended that MLS continue to engage "life cycle thinking" when evaluating their environmental performance beyond the scope of this group project.

11.2.2.2 REGULATORY (GOVERNMENT) CONSIDERATIONS

Awareness of forthcoming government regulations with implications on resource use and sustainability in the industrial laundry sector can assist MLS with making well-informed decisions. The facet of its operations that faces the highest risk of regulation is the company's water use. It is well known that industrial laundering necessitates the use of large amounts of water, and in dry regions such as Central and Southern California, local and state authorities are taking action to increase efficient use of this increasingly scarce resource. The California Department of Water Resources has developed an integrated statewide water management plan in order to manage water resources and plan for future demands. Within this plan, potential future regulations are outlined that would reduce water withdrawal and consumption and increase water quality for California (California Department of Water Resources, 2009). By being prepared for these rulings and attaining compliance levels ahead of time, MLS can better poise itself to become a good corporate citizen and gain an advantage over competitors that may not be as prepared for compliance.

As the California Integrated Water Management Plan (2009) explains, Senate Bill 7 mandates statewide water conservation by requiring urban water suppliers to reduce per capita use by 20 percent by 2020. The directives of this bill may have effects on large-scale water users, such as commercial laundry facilities, in that less water will be available for their consumption. Therefore, it is important that MLS be prepared for these possibilities by taking measures to monitor and improve the water efficiency of their operations. The Integrated Management Plan also discusses the implications Assembly Bill 32 (AB 32) will have on California's water supply. AB 32 creates a statewide GHG emissions limit that would reduce emissions 25 percent by 2020 (California EPA, 2010). The AB 32 Scoping Plan includes measures to reduce the GHGs resulting from water use and wastewater treatment. Measures of the Scoping Plan include reducing GHGs by reducing the energy requirements for providing and using a reliable water supply, and reducing the electricity consumed in transporting and treating water (California Integrated

Water Management Plan, 2009). Additionally, AB 32 holds implications for stationary sources within MLS, such as boilers and dryers, in respect in GHG emission reductions. In order to prepare for these GHG reductions, it is advised that Mission Linen Supply monitor and analyze the use of energy for equipment operation and water transport and treatment, and then identify areas for improvements.

Although pollution was not the subject of this analysis, the chemicals used in MLS' washing operations are subject to government regulations as well. In August 2010, EPA announced plans to potentially include nonylphenol (NP) and nonylphenol ethoxylates (NPE), chemicals widely used in industrial laundry detergents, as listings under Toxic Release Inventories (TRI) as part of the Toxic Substances Control Act (TSCA) (EPA, 2010). NP and NPE are highly toxic to aquatic organisms, and if added to the TRI, facilities would be required to report releases of these chemicals to the environment (Laundry Today, 2010). EPA is also proposing a "significant new use rule" (SNUR) for NP and NPE, which mandates that any company choosing to use these chemicals must submit a "significant new use notice" (SNUN) to EPA 90 days before beginning the use. The companies would be required to install costly equipment to monitor employee exposure to these chemicals and take any other actions mandated by EPA (Laundry Today, 2010). Following this announcement, MLS might examine all of its washroom formulas and identify any that include the use of NP or NPE. If these chemicals are being used, MLS could look to industry publications and/or competitors to identify replacement chemicals that are as effective, but less harmful to the natural and human environment.

11.2.2.3 SCALABILITY TO INDUSTRY

From an industry standpoint, the LCA results and its conclusions and recommendations can serve as the basis for future guidelines and policies by the Textile Rental Services Association (TRSA). At a minimum, the report authors hope the release of an LCA study on industrial laundering can further life cycle thinking within the industry.

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APPENDICES

Appendix A: Data Quality Assessment

Appendix B: LCI Assumptions and Calculations

Appendix C: Sensitivity Analysis

Appendix D: Calculations for CEDA Input and Output Data

APPENDIX A: DATA QUALITY ASSESSMENT

This table was populated based on ISO 14040 standard guidelines for assessing LCA data quality.

Process	**Source**	**Date**	**Geography**	**Uncertainty**
Shirt Creation				
Cotton Cultivation				
Electricity	EcoInvent	2006	US Average	Medium
Gas	EcoInvent	2006	US Average	Medium
Water	EcoInvent	2006	US Average	Medium
Polyester Manufacturing				
Electricity	GaBi	2005	Germany	Medium
Gas	GaBi	2005	Germany	Medium
Water	GaBi	2005	Germany	Medium
Yarn Manufacturing				
Electricity	EDIPTEX	1990s	Denmark	Medium/High
Gas	EDIPTEX	1998-2003	Danish enterprises**	Medium/High
Water	EDIPTEX	1998-2004	Danish enterprises**	Medium/High
Fabric Production (Weaving)				
Electricity	EDIPTEX	1990s	Denmark	Medium/High
Water	EDIPTEX	1998-2002	Danish enterprises**	Medium/High
Pre-Treatment				
Electricity	EDIPTEX	1990s	Denmark	Medium/High
Gas	EDIPTEX	1998-2003	Danish enterprises**	Medium/High
Water	EDIPTEX	1998-2004	Danish enterprises**	Medium/High
Dyeing				

Electricity	EDIPTEX	1990s	Denmark	Medium/High
Gas	EDIPTEX	1998-2003	Danish enterprises**	Medium/High
Water	EDIPTEX	1998-2004	Danish enterprises**	Medium/High
Finishing				
Electricity	EDIPTEX	1990s	Denmark	Medium/High
Gas	EDIPTEX	1998-2003	Danish enterprises**	Medium/High
Water	EDIPTEX	1998-2004	Danish enterprises**	Medium/High
Cut & Sew				
Electricity	EDIPTEX	1990s	Denmark	Medium/High
Transport (road)				
Electricity	ARB/EMFAC	2007	California	Low
Gas	ARB/EMFAC	2007	California	Low
Water	ARB/EMFAC	2007	California	Low
Transport (Ocean)				
Electricity	Eco Invent	2000	unknown	Medium
Gas	Eco Invent	2000	unknown	Medium
Water	Eco Invent	2000	unknown	Medium
Electricity	WECC	2010	US Average	Low
MLS				
Electricity	WECC	2010	Western US	Low
Natural Gas, Processed	NREL	2007	North America	Low
Natural Gas, Combusted in Boiler	NREL	2007	North America	Low

Natural Gas, Combusted in Industrial Equipment	NREL	2007	North America	Low
Electricity	WECC	2010	Western States Grid	Low
Shirt use				
Boilers				
Electricity	Spec Sheet	1970's-present	US	Medium
Gas	Spec Sheet	1970's-present	US	Medium
Water	Spec Sheet	1970's-present	US	Medium
Washers				
Electricity	MLS	2010	Site-specific	Very low
Gas	MLS	2010	Site-specific	Very low
Water	MLS	2010	Site-specific	Very low
Dryers				
Gas	MLS	2010	Site-specific	Very low
Triple Buck Press/Tunnels				
Electricity	Colmac Industry's Spec Sheet	2010	Site-specific	Low
Gas	Colmac Industry's Spec Sheet	2010	Site-specific	Low
Water	Colmac Industry's Spec Sheet	2010	Site-specific	Low
Water Energy Transport				

Santa Barbara	PIER Report	1997/2006	Regionally-specific	Low
Chino	PIER Report	2006	Regionally-specific	Low
Sacramento	PIER Report	2006	Regionally-specific	Low
Oceanside	PIER Report	2005/2006	Regionally-specific	Low
Water Supply				
Electricity	Ecoinvent	unknown	Europe	Medium
Gas	Ecoinvent	unknown	Europe	Medium
Water	Ecoinvent	unknown	Europe	Medium
Transport				
Electricity	ARB/EMFAC	2007	California	Low
Gas	ARB/EMFAC	2007	California	Low
Water	ARB/EMFAC	2007	California	Low
PET in Landfill				
Electricity	BUWAL	1996	Switzerland	High
Gas	BUWAL	1996	Switzerland	High
Water	BUWAL	1996	Switzerland	High

APPENDIX B: LCI ASSUMPTIONS AND CALCULATIONS

TABLE 1: SHIRT CREATION PHASE DATA SOURCES, ASSUMPTIONS AND CALCULATIONS

Shirt Creation	Assumptions	Free Parameters	Calculations
Cotton Production	Data from Eco Invent database, aggregated "US: cotton fibers, at farm [plant production]": Inventory refers to the production of 1 kg cotton fibre respectively cottonseed, both with a moisture content of 6%. Fresh matter yield at 6% moisture: 775 kg/ha cotton fibre and 1144 kg/ha cottonseed. Economic allocation with allocation factor of 87.2% to fibre (exceptions see report).	0.116 kg cotton	Amount of cotton based on mass loss from subsequent processes.
PET Production	Data from PE (GaBi) database, Aggregated "Polyethylene terephthalate granulate (PET, via DMT)" Also assumes Chinese electric grid and power entirely from electricity	0.1968 kg polyester	Amount of polyester based on mass loss from subsequent processes.

Shirt Creation	**Assumptions**	**Free Parameters**	**Calculations**
Polyester Manufacturing	Data from www.fibersource.com, Franklin Associates	0.1968 kg polyester fibers	0.0306 MJ energy required to produce fibers
Yarn Manufacturing	Data taken from: EDIPTEX Environmental Assessement of Textiles, Danish EPA, 2007, and Farrant 2008, output is for one kg spun 35/65 poly/cotton yarn. Estimated mass loss of 20% is used for cotton and 9% for polyester. Electricity data taken from: EDIPTEX Environmental Assessement of Textiles, Danish EPA, 2007. Number listed are for 35/65 cotton/poly yarn production Assumptions: For calculation assume 15 MJ for 770 g garment. Yarn manufacturing process used by US yarn producers is comparable to Danish yarn producers.	cotton = 0.35: Percentage of cotton in each shirt Poly = 0.65: Percentage of polyester in each shirt waste_cotton = 1.2; Percentage of waste for cotton waste_poly = 1.09; Percentage of waste for polyester weight_out = 0.278; Total weight of fabric output to make 1 shirt (kg)	cotton_in = cotton*weight_out*waste_cotton = 0.116; Weight of cotton required to make 1 shirt (kg) poly_in = poly*weight_out*waste_poly = 0.197; Weight of polyester required to make 1 shirt (kg) Electricity: 1.235 MJ, scaled from 2.84 MJ per 770 g work jacket Natural gas: 0.0034 kg, scaled from 0.002 kg per 770 g work jacket. Water: 0.43 kg, scaled from 0.992 per 770 g of spun yarn.

Shirt Creation	Assumptions	Free Parameters	Calculations
Yarn Manufacturing Transportation	Polyester assumed is sourced from China and is shipped via oceanic ship to Long Beach, which is then transported via diesel truck to Spartanburg, SC. Cotton is assumed to be sourced from Texas and is transported via diesel truck to Spartanburg, SC.	Texas to South Carolina: mi = 1174; Miles from Texas to Spartanburg fabric_weight = 0.1167; Weight of fabric (kg) China/Long Beach: Distance = 7306.83; Distance from China to Long Beach (km) poly_weight = 0.1968; Weight of polyester (kg) Long Beach/Spartanburg Distance = 2571.7; Distance from Long Beach to Spartanburg (km) fabric_weight = 0.19681; Weight of fibers (kg)	Transportation- Texas to South Carolina: distance = mi*1.0602 = 1244.7; Distance from Texas to Spartanburg (km) transport = distance*fabric_weight = 145.2; Transportation in kgkm Transportation- China/Long Beach: transport = distance*poly_weight = 1437.98; Transportation in kgkm transport_tkm = transport/1000 = 1.438; Transportation in tkm Transportation- Long Beach/Spartanburg: transport = distance*fabric_weight = 506.15; Transportation in kgkm

Shirt Creation	**Assumptions**	**Free Parameters**	**Calculations**
Weaving	Data taken from: EDPITEX Environmental Assessment of Textiles, Danish EPA, 2007 and Farrant 2008. Mass loss assumed between 3-8%, so 8% was used for calculating fabric weight. Electricity data taken from: EDPITEX Environmental Assessment of Textiles, Danish EPA, 2007. p. 141. Based on energy estimate from result chart. Assumptions: Closed off high speed air jet looms are used in the weaving process for the MLS shirt. No natural gas is used.	Waste = 0.08: Amount of fabric (%) wasted in this step fabric_out = 0.277: Weight of fabric output (kg)	waste_weight = fabric_out*waste = 0.02: Weight of fabric waste (kg) fabric_weight = fabric_out+waste_weight = 0.27: Weight of fabric required to make one shirt Electricity: 0.335 MJ, scaled from 0.92 MJ per 770 g work jacket Water: 0.065 kg, scaled from 0.18 per 770 g of spun yarn.
Pre-treatment	Data taken from: EDPITEX Environmental Assessment of Textiles, Danish EPA, 2007. p. 141. Based on energy estimate from result chart. Assumptions: Pre-treatment process is comparable for the MLS shirt	Fabric weight = 0.257 kg Natural gas, combusted in industrial equipment = 0.0236 m^3 Water = 1.54 kg	Natural gas: 0.019 kg, scaled from 0.057 kg per 770 g work jacket. Water: 1.54 kg, scaled from 4.63 per 770 g of fabric.

Shirt Creation	**Assumptions**	**Free Parameters**	**Calculations**
Dyeing	Data taken from: EDPITEX Environmental Assessment of Textiles, Danish EPA, 2007. p. 141. Based on energy estimate from result chart. Assumptions: Dyeing process is comparable for the MLS shirt	Fabric = 0.257 kg Natural gas, combusted in industrial equipment = 0.0355 m^3 Water = 4.52 kg	Natural gas: 0.028 kg, scaled from 0.086 kg per 770 g work jacket. Water: 4.52 kg, scaled from 13.5 per 770 g of spun yarn.
Finishing	Waste estimated at 3% for wet treatments. Data taken from: EDPITEX Environmental Assessment of Textiles, Danish EPA, 2007. p. 141. Based on energy estimate from chart. Assumptions: Finishing process is comparable for the MLS shirt.	Waste = 0.03: Amount of fabric (%) wasted in this step Shirt = 0.2497: Weight of fabric from previous step (kg) Fabric = 0.257191 kg Power = 0.00752 MJ Natural gas = 0.0172 m3 Water = 0.30132 kg	waste_weight = shirt*waste = 0.007491: Weight of fabric waste (kg) fabric_weight = shirt+(waste*shirt) = 0.257: Weight of fabric required to make one shirt Electricity: 0.0075 MJ, scaled from 0.0225 MJ per 770 g work jacket Natural gas: 0.013 kg, scaled from 0.0415 kg per 770 g work jacket. Water: 0.301 kg, scaled from 0.9 per 770 g of spun yarn.

Shirt Creation	Assumptions	Free Parameters	Calculations
Cut and Sew	VF imagewear estimates loss at 8-10%, so 10% was used. Electricity data from Farrant 2008. Assumes only electricity use.	Waste = 0.1: Amount of fabric (%) wasted in this step Shirt = 0.227: Weight of shirt (kg) Power = 0.10987 MJ	waste_weight = shirt*waste = 0.0227: Weight of fabric waste (kg) fabric_weight = shirt+(waste*shirt) = 0.2497: Weight of fabric required to make one shirt Electricity: 0.10987 MJ, scaled from 0.338 MJ per 770 g work jacket
Cut and Sew Transportation	Cut and Sew processes are assumed to take place in Haiti, so fabric is transported via diesel truck from Spartanburg, SC to Miami, FL. Then it is assumed to travel from Miami to Port-Au-Prince in Haiti via oceanic ship and back.	<u>Spartanburg/Miami:</u> Distance = 1163.55; Distance from Spartanburg to Miami FL (km) fabric_weight = 0.2497; Weight of fabric (kg) <u>Miami/Haiti:</u> Distance = 1142.6; Distance from Miami FL to Port-Au-Prince, Haiti (km) fabric_weight = 0.2497; Weight of fabric (kg)	<u>Transportation- Spartanburg/Miami:</u> transport = distance*fabric_weight = 290.53; Transportation in kgkm <u>Transportation- Miami/Haiti:</u> rt_distance = distance*2 = 2285.2; Round trip distance from Haiti to Miami (km) transport = rt_distance*fabric_weight = 570.614; Transportation in kgkm transport_tkm = transport/1000 = 0.5706; Transportation in tkm

Shirt Creation	**Assumptions**	**Free Parameters**	**Calculations**
Final Delivery	Once the shirts are completed, it was assumed they are transported from Miami, FL to Tupelo, MS and finally Chino, CA via diesel truck.	Distance = 3173.6; Distance from Tupelo to Chino (km) distance1 = 1454.8; Distance from Miami to Tupelo, Miss (km) fabric_weight = 0.227; Weight of fabric (kg)	Transportation- Miami/Tupelo/MLS: distance_tot = distance+distance1 = 4628.4; Total distance from Miami to Chino (km) transport = distance_tot*fabric_weight = 1050.6; Transportation in kgkm
Shirt Disposal (EoL)	Assumes an average distance of 50 km to the nearest landfill for disposal.	shirt_wt = 0.227: Weight of single shirt (kg) km = 50: Average distance to landfill	transport = shirt_wt*km = 11.35: Transportation (kgkm)

TABLE 2: USE PHASE DATA SOURCES, ASSUMPTIONS AND CALCULATIONS (BOILER FOR WATER HEATING)

Boiler	**Source and Assumptions**	**Electricity**	**Natural Gas**	**Water**
Hurst 500 hp **Sacramento**	Steam requirements from (industrialboiler.com/boilers/boiler-sales.aspx) Electrical requirements are a Cleaver Brooks 500 hp boiler (1979) Washer load size and	Shirt_weight = 0.5 lbs Load_weight = 450 lbs steam = 17600: steam produced (lb/hr) Percent_weight = Shirt_weight/Load_weight: Percent of load represented by one shirt. Washer_water = 397: Units in gallons. Amount of hot	hp = 500: Boiler hp gas = hp*2545: natural gas use (BTU/h) gas_shirt = gas*Washer_percent*Percent weight:	water_shirt = Washer_water*Percent_weight: Water requirements for one shirt (gallons)

Boiler	**Source and Assumptions**	**Electricity**	**Natural Gas**	**Water**
	water use based on 450 Ellis washer formulas	water used by washer. washer_percent = Washer_water/water: Units in gallons. Amount of hot water used by washer. power = 50*550: Amp * Volt = Watts = Joules/sec power_time = power*60*60: Conversion J/s to J/h. power time* Washer percent* percent weight	Gas requirements for one shirt (BTU)	
Superior 250 hp **Santa Barbara**	Electric requirements from: http://www.genemco.com/catalog/firetube.html (Cleaver Brooks 250 hp boiler spec sheet) Steam requirements from: http://www.boilerspec.com/speci-fire_pdf/a2-cb.pdf (Cleaver Brooks 250 hp Boiler spec sheet) Washer load size and water use based on 450 Ellis washer formulas	Shirt_weight = 0.5: Units in lbs. Weight of one shirt. Load weight = 450: Units in lbs. Total load of washer. Washer water = 397: Units in gallons. Hot water used by washer. Steam = 8625: steam produced (lb/hr) steam_liters = steam*0.45359237: 1 lb = 0.45359237 kg, 1 kg ~ 1 L Conversion to L/hr Steam_gallons = 0.264*steam_liters: 1 liter = 0.264 gallons. Conversion from liters to gallons. washer_percent = washer_water/Steam_gallons: Units in gallons. Percent of hot water used by washer. Power = 220*21: Amp * Volt = Watts = Joules/sec power_time = power*60*60: electrical requirements for 1 hour (J) Percent_weight = Shirt_weight/Load_weight: Percent of load represented by one shirt.	hp = 250: Boiler hp Gas = hp*2545: natural gas use (BTU/h) Gas shirt = gas*washer percent*Percent weight: Natural gas requirements for 1 shirt (BTU)	Daily shirts = 292: Average daily number of shirts at Santa Barbara facility hours = 8: hours of boiler operation shirt_hr = daily_shirts/hours: Amount of shirts per hour that are laundered at Santa Barbara Shirt_water = washer_water*Percent_weight: Units in gallons. Amount of water allocated to one shirt. water = steam_liters*0.264:

Boiler	Source and Assumptions	Electricity	Natural Gas	Water
		power_shirt = power_time*washer_percent*Percent_weight: Electrical requirements for 1 shirt (J)		Conversion to gallons/hr water_shirt = water/shirt_hr: Water requirements for one shirt at Santa Barbara (gallons)
Superior 400 hp **Chino**	Electrical requirements source : http://www.wabashpower.com/400HPCleaverBrooks.html (Cleaver Brooks 400 hp boiler), assuming a 20hp blower Steam requirements source: http://www.wabashpower.com/400HPCleaverBrooks.html (Cleaver Brooks 400Hp Boiler)	Shirt_weight = 0.5: Units in lbs. Steam = 13800: steam produced (lb/hr) steam_liters = steam*0.45359237 = 6259.574706: 1 lb = 0.45359237 kg, 1 kg ~ 1 L Conversion to L/hr water = steam_liters*0.264 = 1652.5277: Conversion to gallons/hr daily_shirts = 10316: Average daily number of shirts at Oceanside shirt_hr = daily_shirts/hours = 1289.5: Number of shirts laundered in one hour Washer_water = 397: Units in gallons. Amount of hot water used by washer. Load_weight = 450: Units in lbs. Percent_weight = Shirt_weight/Load_weight = 0.0011: Percent of load represented by one shirt. Water_percent = Washer_water/water = 0.2402:	Hp = 400: Boiler hp Gas = hp*2545 = 1018000: natural gas use (BTU/h) gas_shirt = gas*Water_percent *Percent_weight = 271.73: Gas requirements for one shirt (BTU)	water_shirt = Washer_water*Percent_weight = 0.441: Water requirements for one shirt (gallons)

Boiler	Source and Assumptions	Electricity	Natural Gas	Water
		Percent of water used by washer. power = (blower_hp*746)/1000 = 14.92: Electrical requirements calculation: 20 hp * 746W/1000 = kWh blower_hp = 20: Blower hp power_shirt = power*Water_percent*Percent_weight = 0.003982: Electrical requirements for one shirt (kWh)		
Superior 475 hp **Chino**	Electrical and water requirements from source: http://www.boilerspec.com/speci-fire_pdf/a2-cb.pdf (Cleaver Brooks 500 Hp Boiler spec sheet)	Shirt_weight = 0.5: Units in lbs. Load_weight = 450: Units in lbs. Steam = 17250: steam produced (lb/hr) Percent_weight = Shirt_weight/Load_weight = 0.00111: Percent of load represented by one shirt. Power = 50*550*60*60 = 99000000: Units in J/h Washer_water = 397: Units in gallons. Amount of hot water used by washer. Water = steam_liters*0.264 = 2065.66: Conversion to gallons/hr steam_liters = steam*0.45359237 = 7824.4683825: 1 lb = 0.45359237 kg, 1 kg ~ 1 L Conversion to L/hr Washer_percent = Washer_water/water = 0.192190421799289: Percent of water used by washer. power_shirt = power*Washer_percent*Percent_weight = 21140.94: Electrical requirements for one shirt (J)	hp = 475: Boiler hp Gas = hp*2545 = 1208875: natural gas use (BTU/h) gas_shirt= gas*Washer_percent*Percent_weight = 258.1491: Gas requirements for one shirt (BTU)	water_shirt = Washer_water*Percent_weight = 0.4411: Water requirements for one shirt (gallons)

Boiler	Source and Assumptions	Electricity	Natural Gas	Water
Dixon 300 hp **Sacramento**	Energy data from: http://www.genemco.com/catalog/firetube.html (Cleaver Brooks 300 hp boiler spec sheet) Steam requirements from: http://www.boilerspec.com/speci-fire_pdf/a2-cb.pdf (Cleaver Brooks 300 Hp Boiler spec sheet)	Shirt_weight = 0.5: Units in lbs. Load_weight = 450: Units in lbs. Percent_weight = Shirt_weight/Load_weight = 0.001111: Percent of load represented by one shirt. Steam = 10350: steam produced (lb/hr) steam_liters = steam*0.45359237 = 4694.6810295: 1 lb = 0.45359237 kg, 1 kg ~ 1 L Conversion to L/hr water = steam_liters*0.264 = 1239.395791788: Conversion to gallons/hr washer_water = 397: Units in gallons. Hot water used by washer. Electric= 330*25 = 8250: Amp * Volt = Watts = Joules/sec elec_hour = electric*60*60 = 29700000: Conversion J/s to J/h. Percent_water = washer_water/water = 0.3203: Percent of hot water used by washer. power_shirt = elec_hour*Percent_water*Percent_weight = 10570.47: Electricity requirements for one shirt (J)	hp = 300: Boiler hp gas = hp*2545 = 763500: Conversion to BTU/h gas_shirt = gas*Percent_water*Percent_weight = 271.735: Gas requirements for one shirt (BTU)	water_shirt = washer_water*Percent_weight = 0.4411: Water requirements for one shirt (gallons)
Dixon 175 hp **Oceanside**	Natural gas calculated from boiler hp, power and water requirements estimated from Cleaver brooks 175 hp boiler	Shirt_weight = 0.5: Units in lbs. Load_weight = 900: Units in lbs. Percent_weight = Shirt_weight/Load_weight =	hp = 175: boiler horsepower gas = hp*2545 = 445375: Units in	water_shirt = water_washer*Percent_weight = 0.2389: Water requirements for one shirt at

Boiler	Source and Assumptions	Electricity	Natural Gas	Water
	(1979) Source: http://www.genemco.com/catalog/firetube.html (Cleaver Brooks 175 hp boiler spec sheet) Allocated for the Ellis 900 washer	0.0005556: Percent of load represented by one shirt. Steam = 6000: lb/hour steam_L = steam*0.45359237 = 2721.55422: Conversion to L/hr (1 lb=0.45359237 kg and 1 kg ~ 1 L) water = steam_L*0.264 = 718.49: Conversion to gallons/hour water_washer = 430: Units in gallons. Hot water used by washer. water_percent = water_washer/water = 0.59847: Percent of heated boiler water used by washer. electric = 230*43 = 9890: Amp * Volt = Watts = Joules/sec elec_hour = electric*60*60 = 35604000: Conversion from J/s to J/h. power_shirt = elec_hour*water_percent*Percent_weight = 11837.877: Power requirements for one shirt at Oceanside (J)	BTU/h gas_washer = water_percent*gas = 266546.738: Amount of gas used to heat water used in washer in BTU/h. gas_shirt = gas_washer*Percent_weight = 148.0815: Gas requirements for one shirt at Oceanside (BTU)	Oceanside (gallons)
Dixon 175 hp **Oceanside**	Natural gas calculated from boiler hp, power and water requirements estimated from Cleaver brooks 175 hp boiler (1979) Source: http://www.genemco.co	Shirt_weight = 0.5: Units in lbs. Steam= 6000: lb/hour Load_weight = 585: Units in lbs. steam_L = steam*0.45359237 = 2721.55: Conversion to L/hr (1 lb=0.45359237 kg and 1 kg ~ 1 L) Electric = 230*43 = 9890: Amp * Volt = Watts =	Hp = 175: boiler horsepower Gas= hp*2545 = 445375: Units in BTU/h gas_washer = water_percent*gas	shirt_hr = daily_shirts/hours = 136.75: Shirts laundered per hour at Oceanside daily_shirts = 1094: Average daily shirts at

Boiler	Source and Assumptions	Electricity	Natural Gas	Water
	m/catalog/firetube.html (Cleaver Brooks 175 hp boiler spec sheet) Allocated for the Ellis 675 washer	Joules/sec elec_hour = electric*60*60 = 35604000: Electricity required (J) 60 sec * 60 min water = steam_L*0.264 718.49031408: Conversion to gallons/hour water_washer = 107: Amount of hot water used by Ellis 675 washer. water_percent = water_washer/water = 0.14892: Percent of heated boiler water used by washer. Percent_weight = Shirt_weight/Load_weight = 0.0008547: Percent of load represented by one shirt. Percent_water = water_washer*Percent_weight = 0.09145: Units in gallons. Amount of boiler water used by one shirt. power_shirt = elec_hour*water_percent*Percent_weight = 4531.85: Units in Joules/h. Power requirements for one shirt at Oceanside (J)	= 66326.746: Amount of gas used to heat water used in washer in BTU/h. gas_shirt = gas_washer*Percent_weight = 56.689: Gas requirements for one shirt at Oceanside (BTU)	Oceanside Hours = 8: Hours worked per day water_shirt = water/shirt_hr = 5.254: Water requirements for one shirt at Oceanside (gallons)
Boiler Average **Sacramento/ Oceanside**	Assumes an equal percentage contribution from both boilers	water_475 = 0.5: percent of water from Superior 475 hp boiler water_400 = 0.5: percent of water from Superior 400 hp boiler water = water_400+water_475 = 1: Value must =1		

TABLE 3: USE PHASE DRYER AND TUNNEL SOURCES, ASSUMPTIONS AND CALCULATIONS

Dryers and Tunnels	Source and Assumptions	Electricity	Natural Gas	Water
Colmac Tunnel CTU-235 **Chino**	All calculations based on data taken from Colmac Finishing Tunnel CTU-235 Specification Sheet (December 1991).	Power = (7.5*746)/1000 = 5.595: Units in Kwh. 7.5 hp required. 1 hp = 746 watts. Tunnel_Capacity = 2500: Colmac Tunnel can process 2500 shirts per hour Shirt_power = Power/Tunnel_Capacity = 0.002238: Electricity used by one shirt in Kwh Shirt_powerMJ = Shirt_power*3.6 = 0.0080568: Conversion from Kwh to MJ, where 1 Kwh = 3.6 MJ.	Gas_btu = 600000: Units in BTU/hr. Shirt_gas = Gas_btu/Tunnel_Capacity = 240: Natural gas used by one shirt in BTU/hr. Shirt_MJ = Shirt_gas*0.001055 = 0.2532: Natural gas used by one shirt in MJ/hr.	Steam_liters = 266: Units L/hr. 1L=~1Kg. Water = Steam_liters*.264 = 70.224: Conversion to gallons/hr. Steam = 266: Units in Kg/hr. Shirt_water = Water/Tunnel_Capacity = 0.0280896: Amount of water in gallons used by one shirt.
Colmac Triple Buck Press **Santa Barbara**	Calculations based on Colmac Triple Buck Shirt Press Specification Sheet.	Press_power = 3.976: Units in Kwh Press_MJ = Press_power*3.6 = 14.3136: Conversion from Kwh to MJ/h, where 1Kwh = 3.6 MJ. Press_Capacity = 240: Shirts per hour Shirt_power= Press_MJ/Press_Capacity= 0.05964: Amount of electricity used by one shirt in MJ.	N/A	Steam_liter = 157: Units in L/hr, where 1 L = 1 Kg. Water = Steam_liter*0.264 = 41.448: Conversion from L/hr to gallons/hr. Shirt_water = Water/240 = 0.1727: Amount of water in gallons used by one shirt. Steam = 157: Units in Kg/hr

Dryers and Tunnels	**Source and Assumptions**	**Electricity**	**Natural Gas**	**Water**
Colmac Tunnel 2000-G **Sacramento**	All calculations based on data taken from Colmac Finishing Tunnel 2000-G, referencing the Colmac CFS 2100-5 G/S-X Specification Sheet	Power = 7.46: Units in Kwh. Shirt_power = Power/Tunnel_Capacity = 0.001492: Electricity used by one shirt in Kwh Tunnel_Capacity = 5000: Colmac 2100 Tunnel can process 5000 shirts per hour	Gas_btu = 2000000: Units in BTU/hr. Shirt_MJ = Shirt_gas*0.001055 = 0.422: Natural gas used by one shirt in MJ/hr. Shirt_gas = Gas_btu/Tunnel_Capacity = 400: Natural gas used by one shirt in BTU/hr.	Steam = 314: Units in Kg/hr. Steam_liters = 314: Units L/hr. 1L=~1Kg. Water = Steam_liters*.264 = 82.896: Conversion to gallons/hr. Shirt_water = Water/Tunnel_Capacity = 0.0165792: Amount of water in gallons used by one shirt.
CLM 400 Gas Tumbler **Sacramento** **Santa Barbara**	All calculations based on Mission Linen Services Gas Tumbler Log. Total load weight is assumed to be 400 lbs.	Shirt_weight = 0.5: Weight of one shirt in lbs Total_load = 400: Total weight of load in lbs (assumed). Gas_CCF = 1.65: Units in CCF Natural gas. Gas_therm = Gas_CCF*1.0250 = 1.69125: Conversion from CCF Natural Gas to Therms Gas_btu = Gas_therm*100000 = 169125: Conversion from Therms to BTUs. Percent_load = Shirt_weight/Total_load= 0.00125: Percent of total weight represented by	N/A	N/A

Dryers and Tunnels	Source and Assumptions	Electricity	Natural Gas	Water
		one shirt. Shirt_energy = Percent_load*Gas_btu = 211.41: Amount of energy used by one shirt.		
Colmac Tunnel 2100-3 **Oceanside**	All calculations based on data taken from Colmac CFS 2100-3 G/S-X Specification Sheet.	Power = 8.83: Units in Kwh. Tunnel_Capacity = 5000: Colmac Tunnel can process 5000 shirts per hour. Shirt_power = Power/Tunnel_Capacity = 0.001766: Electricity used by one shirt in Kwh	Gas_btu = 600000: Units in BTU/hr. Shirt_gas = Gas_btu/Tunnel_Capacity = 120: Natural gas used by one shirt in BTU	Steam = 314: Units in Kg/hr. Steam_liters = 314: Units L/hr. 1L=~1Kg. Water = Steam_liters*.264 = 82.896: Conversion to gallons/hr. Shirt_water = Water/Tunnel_Capacity = 0.0165792: Amount of water in gallons used by one shirt.

TABLE 4: USE PHASE WASHING MACHINE SOURCES, ASSUMPTIONS AND CALCULATIONS (ELECTRICITY N/A)

Washing Machines	Source and Assumptions	Natural Gas	Water
Ellis 450 **Santa Barbara** **Sacramento** **Chino**	All calculations based on Mission Linen Services' wash formula I-E3 Colored Garments Ellis 450 WE	Shirt_weight = 0.5: Weight of one shirt in lbs. Total_load = 450: Total weight in lbs of laundered load. Percent_weight = Shirt_weight/Total_load = 0.00111: Precent of total weight represented by one shirt.	Water_Hot = 397: Units in gallons. Amount of hot water used in laundering. Water = 582: Units in gallons. Amount of cold water used in laundering. Shirt_water = Percent_weight*Water = 0.64667: Amount of cold water used per

Washing Machines	**Source and Assumptions**	**Natural Gas**	**Water**
		Gas_therms = 2.37: Units in Therms. Gas_btu = Gas_therms*100000 = 237000: Conversion from therms to BTUs. Gas_MJ = Gas_btu*0.001055 = 250.035: Conversion from BTUs to Megajoules. Shirt_energy = Percent_weight*Gas_MJ = 0.2778167: Amount of energy used by one shirt (MJ)	shirt in gallons. Shirt_Hotwater = Percent_weight*Water_Hot = 0.44111: Amount of hot water used per shirt in gallons.
Ellis 675 **Oceanside**	All calculations taken from Mission Linen Services' wash formula I-C1 Color D/C Garments Ellis 675 Grey.	Shirt_weight = 0.5: Weight of one shirt in lbs. Load_total = 585: Weight of total wash load in lbs. Gas_therms = 0.45: Units in Therms Gas_btu= Gas_therms*100000 = 45000: Conversion from Therms to BTUs Gas_MJ = Gas_btu*0.001055 = 47.475: Conversion from BTUs to Megajoules Percent_load = Shirt_weight/Load_total = 0.0008547: Precentage of total weight represented by one shirt. Shirt_energy = Percent_load*Gas_MJ = 0.04057: Amount of energy in MJs used by one shirt.	water_hot = 107: Units in gallons. Amount of hot water used in laundering one load. Water = 324: Units in gallons. Amount of water used in laundering one load. Shirt_water= Percent_load*water = 0.2769: Amount of water in gallons used by one shirt. shirt_waterhot = Percent_load*water_hot = 0.09145: Amount of hot water in gallons used by one shirt
Ellis 900 **Oceanside**	All calculations are based on data taken from the wash formula for Mission Linen Services' I-E2 White D/C Garments Ellis	Total_load = 900: total weight of load in lbs. Shirt_weight = 0.5: Weight of one shirt in lbs. Percent_load = Shirt_weight/Total_load = 0.0005556: Precentage of total weight represented by one shirt.	Water_hot = 430: Units in gallons. Amount of hot water used in laundering one load Water = 925: Units in gallons. Amount of cold water used in laundering one load Waterhot_shirt = Percent_load*Water_hot

Washing Machines	Source and Assumptions	Natural Gas	Water
	900 Black.	Gas = 2.8: Units in Therms Gas_btu = Gas*100000 = 280000: Conversion from Therms to BTUs Gas_MJ = Gas_btu*0.001055 = 295.4: Conversion from BTUs to Megajoules Shirt_energy = Percent_load*Gas_MJ = 0.16411: Amount of gas in MJs used by one shirt.	= 0.23889: Amount of hot water needed to launder one shirt in gallons. Water_shirt = Percent_load*Water = 0.513889: Amount of cold water needed to launder one shirt in gallons.

TABLE 5: USE PHASE WATER ENERGY TRANSPORT SOURCES, ASSUMPTIONS, AND CALCULATIONS

Water Energy Transport	Assumptions
Santa Barbara	Water_AF = 3276.64: Energy in kWh required to transport 1 Acre Foot.
Sacramento	Water_AF = 1140.4: Energy in kWh to transport 1 Acre Foot
Oceanside	Water_AF = 3296.2: Energy in kWh required to transport 1 Acre Foot of water.
Chino	Water_AF= 3620.1: Energy in kWh to transport 1 Acre Foot of water.

TABLE 6: USE PHASE TRANSPORTATION ASSUMPTIONS AND CALCULATIONS

Transportation (Distribution)	Free Parameters/Assumptions	Calculations
Oceanside	Mi = 5740: Miles driven weekly Routes = 13: Daily routes shirt_lb = 0.5: Weight of single shirt (lb) shirts = 1094:Average daily number of D/C shirts Total_lb = 40194: Average daily pounds of laundry	Km = (mi*1.602)/5 = 1839.096: Kilometers driven daily shirt_weight = shirt_lb/2.204 = 0.2268: Weight of single shirt (kg) SingleShirt_km = km/routes= 141.468923076923: Share of km allocated to single shirt Transport = shirt_weight*SingleShirt_km = 32.093: Transport (kgkm)
Santa Barbara	mi = 1150: Miles driven weekly routes = 7: Daily routes Shirts= 292: Average daily number of D/C shirts shirt_lb = 0.5: Weight of single shirt (lb) Total_lb = 21574: Average daily pounds of laundry	SingleShirt_km = km/routes = 52.6371: Share of km allocated to single shirt shirt_weight = shirt_lb/2.204 = 0.22686: Weight of single shirt (kg) km = (mi*1.602)/5 = 368.46: Kilometers driven daily transport = shirt_weight*SingleShirt_km = 11.941: Transport (kgkm)
Sacramento	mi = 5740: Miles driven weekly routes = 13: Daily routes Shirts = 16015: Average daily number of D/C shirts	SingleShirt_km = km/routes = 141.46: Share of km allocated to single shirt shirt_weight = shirt_lb/2.204 = 0.2268: Weight of single shirt (kg)

Transportation (Distribution)	Free Parameters/Assumptions	Calculations
	shirt_lb = 0.5: Weight of single shirt (lb) Total_lb = 106776: Average daily pounds of laundry Assumes mileage and number of routes equal to Oceanside, no data available.	km = (mi*1.602)/5 = 1839.096: Kilometers driven daily transport = shirt_weight*SingleShirt_km = 32.0936: Transport (kgkm)
Chino	mi = 5740: Miles driven weekly routes = 13: Daily routes Shirts = 10316: Average daily number of D/C shirts shirt_lb = 0.5: Weight of single shirt (lb) Total_lb = 90264: Average daily pounds of laundry Assumes mileage and number of routes equal to Oceanside, no data available.	SingleShirt_km = km/routes = 141.4689: Share of km allocated to single shirt shirt_weight = shirt_lb/2.204 = 0.2268: Weight of single shirt (kg) km = (mi*1.602)/5 = 1839.096: Kilometers driven daily transport = shirt_weight*SingleShirt_km = 32.093: Transport (kgkm)

APPENDIX C: SENSITIVITY ANALYSIS

TABLE 1: SHIRT FUNCTIONAL UNIT

Parameter	**Energy** **[net calorific value]** (MJ)		**Global Warming Potential** (**kg CO2-Equiv.**)		**Volume** (**liters**)	
	-50% St. Dev	+50% St. Dev	-50% St. Dev	-50% St. Dev	+50% St. Dev	-50% St. Dev
Lifespan of shirt	-15.60%	18.90%	-18.90%	18.90%	-18.60%	18.60%

TABLE 2: YARN MANUFACTURING

Parameters	**Energy** **[net calorific value]** (MJ)		**Global Warming Potential** (**kg CO2-Equiv.**)		**Volume** (**liters**)	
	-50% St. Dev	+50% St. Dev	-50% St. Dev	-50% St. Dev	+50% St. Dev	-50% St. Dev
% cotton	-25.50%	25.50%	-9.15%	9.15%	0%	0%
% poly	-22.70%	22.70%	-18%	18%	-6.93%	6.93%

TABLE 3: TRANSPORTATION

Process	**Parameters**	**Energy [net calorific value] (MJ)**		**Global Warming Potential (kg CO2-Equiv.)**		**Volume (Liters)**	
		-50% St. Dev	+50% St. Dev	-50% St. Dev	-50% St. Dev	+50% St. Dev	-50% St. Dev
Yarn - Polyester (**China/Long Beach, CA via boat**)	distance	-1.79%	1.79%	-0.39%	0.39%	0%	0%
Yarn - Cotton (**Texas to South Carolina via truck**)	distance	-0.01%	0.01%	-0.60%	0.60%	0%	0%
Cut & Sew (**Spartanburg, SC/Miami, FL via truck**)	distance	0%	0%	-1.67%	1.67%	0%	0%
Cut & Sew (**Miami, FL/Haiti via boat**)	distance	-1.25%	1.25%	-0.27%	0.27%	0%	0%
Final Delivery (**Miami, FL/Tupelo, MS via truck**)	distance	-0.05%	0.05%	-2.97%	2.97%	0%	0%
Final Delivery (**Tupelo, MS/Chino, CA via truck**)	Distance #2	-0.02%	0.02%	-1.36%	1.36%	0%	0%

TABLE 4: CHINO FACILITY

Process with specific equipment	**Parameters**	**Energy [net calorific value] (MJ)**		**Global Warming Potential (kg CO2-Equiv.)**		**Volume (liters)**	
Water heating (boilers)		-50% St. Dev	+50% St. Dev	-50% St. Dev	-50% St. Dev	+50% St. Dev	-50% St. Dev
Superior 400 HP	hp	-0.02%	0.02%	-5.45%	5.45%	0%	0%
Superior 400 HP	steam	0.17%	-0.06%	12.40%	-4.14%	0%	0%
Superior 475 HP	hp	-0.02%	0.02%	-5.18%	5.18%	0%	0%
Superior 475 HP	steam	0.24%	-0.08%	12.60%	-4.20%	0%	0%
Washing							
Ellis 450 Washer	Gas	-0.03%	0.03%	-10.60%	10.60%	0.00%	0.00%
Ellis 450 Washer	Total load weight	93.60%	-31.20%	57.00%	-19.00%	97.50%	-32.50%
Ellis 450 Washer	Water	-27.70%	27.70%	-3.23%	3.23%	-29.00%	29.00%
Ellis 450 Washer	Hot water	-19.10%	19.10%	-14.70%	14.70%	-19.80%	19.80%
Drying							
Colmac Tunnel CTU-235	Tunnel Capacity	2.61%	-0.87%	17.50%	-5.85%	2.52%	-0.84%

Colmac Tunnel CTU-235	Gas	-0.03%	0.03%	-7.78%	7.78%	0.00%	0.00%
Colmac Tunnel CTU-235	Steam	-1.20%	1.20%	-0.14%	0.14%	-1.26%	1.26%

TABLE 5: SACRAMENTO FACILITY

Process with specific equipment	**Parameters**	**Energy [net calorific value] (MJ)**		**Global Warming Potential (kg CO2-Equiv.)**		**Volume (liters)**	
Water heating (boilers)		-50% St. Dev	+50% St. Dev	-50% St. Dev	-50% St. Dev	+50% St. Dev	-50% St. Dev
Hurst 500 HP Boiler	hp	-0.02%	0.02%	-4.99%	4.99%	0%	0%
Hurst 500 HP Boiler	steam	0.22%	-0.07%	12.00%	-4.01%	0%	0%
Dixon 300 HP Boiler	hp	-0.02%	0.02%	-5.09%	5.09%	0%	0%
Dixon 300 HP Boiler	steam	0.13%	-0.04%	11.20%	-3.74%	0%	0%
Washing							
Ellis 450 Washer	Gas	-0.03%	0.03%	-9.88%	9.88%	0%	0%
Ellis 450 Washer	Total load	88.10%	-29.40%	47.20%	-15.70%	100.00%	-33.30%
Ellis 450 Washer	Water	-26.10%	26.10%	-1.25%	1.25%	-29.70%	29.70%
Ellis 450 Washer	Hot water	-17.90%	17.90%	-12.50%	12.50%	-20.30%	20.30%
Drying							

Colmac Tunnel 2000-G	Tunnel Capacity	0.77%	-0.26%	15.60%	-5.19%	0%	0%
Colmac Tunnel 2000-G	Power	-0.02%	0.02%	-0.27%	0.27%	0%	0%
Colmac Tunnel 2000-G	Steam	-0.33%	0.33%	-0.02%	0.02%	0%	0%
CLM 400 Gas Tumbler	Gas	-0.01%	0.01%	-3.58%	3.58%	0%	0%
CLM 400 Gas Tumbler	Total load	0.02%	-0.01%	7.15%	-2.38%	0%	0%

APPENDIX D: CALCULATIONS FOR CEDA INPUT AND OUTPUT DATA

SHIRT CREATION

Men's broadcloth short sleeve shirt (Consumer's price 2011)[1]	$15.50
Consumer's price (2002)[2]	$12.60
Consumer to producer's price conversion	0.7656
Producer's Price (2002)	**$9.65**
Cut and sew apparel contractors (NAICS code 315210)	
Total kg CO2-equiv.	**4.5**

[1] *www.missionlinen.com*

[2] *www.bls.gov/data/inflation_calculator.htm*

SHIRT USE (LAUNDRY)

University of Kentucky Contract: Men's button front short sleeve 65% polyester/35% cotton shirt (Consumer's price in 2002)[3]	$0.37	University of Wisconsin-Madinson Contract: Short sleeve 65% polyester/35% cotton work shirt (Consumer's price in 2011)[4]	$0.41
		Consumer's price in 2002[2]	$0.33
Consumer to producer's price conversion	1	Consumer to producer's price conversion	1
Producer's Price in 2002	$0.37	Producer's Price in 2002	$0.33
Average producer's price in 2002	**$0.35**		
Dry-cleaning and laundry services (NAICS code 812300)			
Total kg CO2-equiv.	**5.2**		

[3] *www.uky.edu/Purchasing/uk-0212-2pct.pdf*

[4] *www.bussvc.wisc.edu/purch/contract/wp5194.html*

SHIRT DISPOSAL (END-OF-LIFE):

7,500 shirts disposed per year @ $2000 (Consumer's price in 2010)[5]	$0.27
Consumer's price (2002)[2]	$0.22
Consumer to producer's price conversion	1
Producer's Price (2002)	**$0.22**
Waste management and remediation services (NAICS code 562000)	
Total kg CO2-equiv.	**0.5**

[5] *Personal communications with MLS, Jan 05, 2011*